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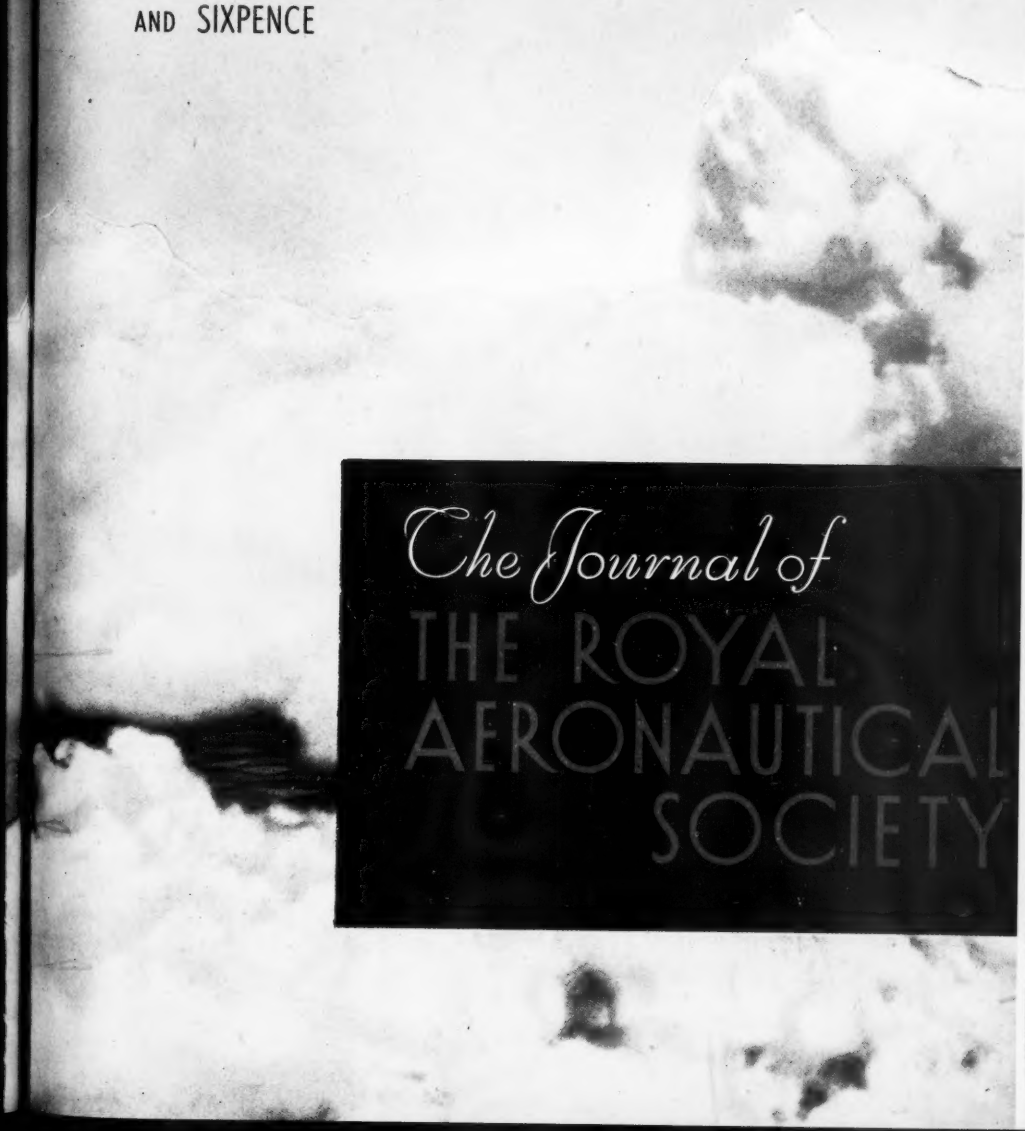

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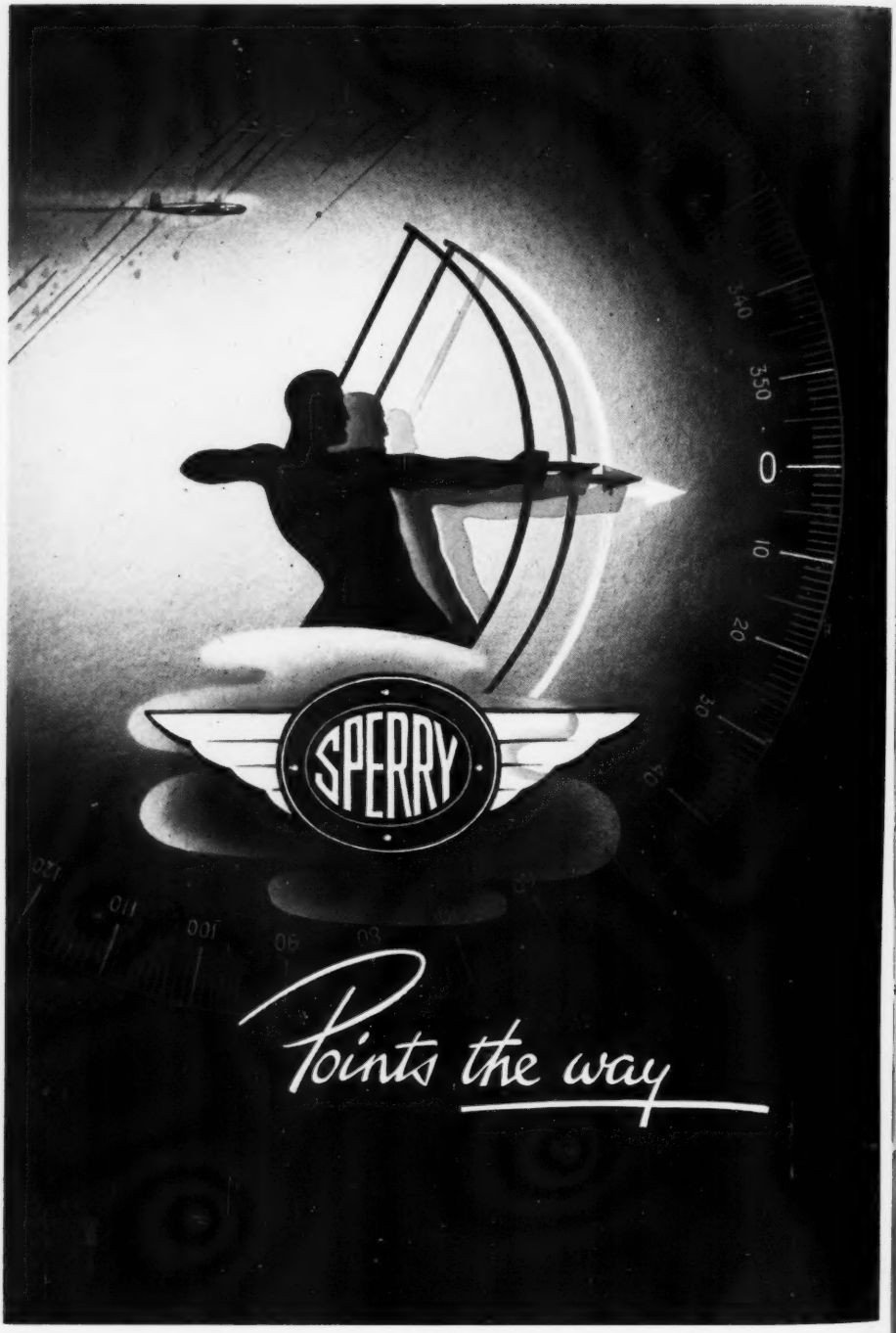
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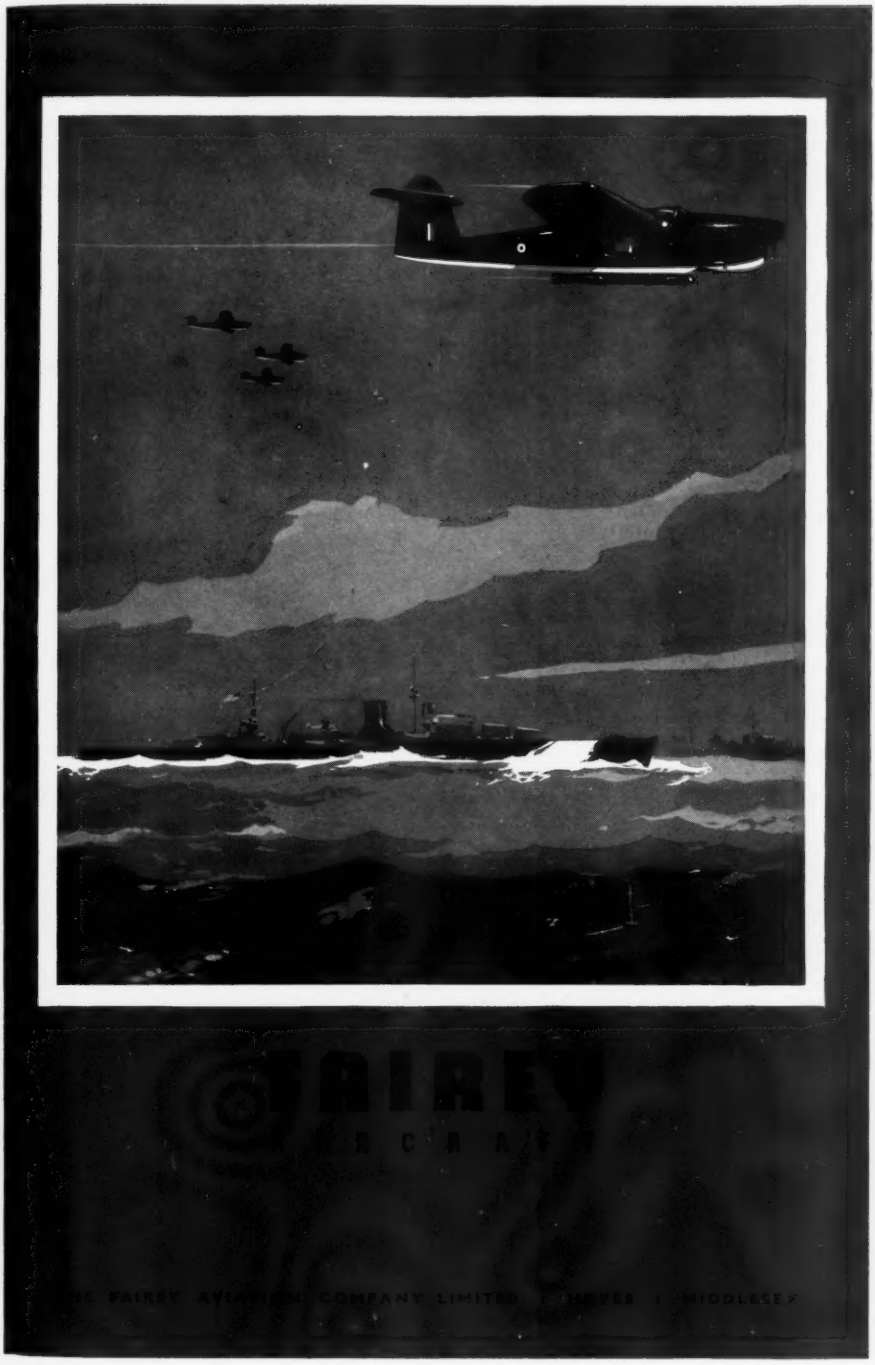
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THE SOCIETY'S PRIZES

The Society offers a number of valuable prizes, most of them annually. Full particulars of the conditions attaching to the awards of these prizes may be obtained on application

Society's Gold Medal

This is the highest honour which the Society can confer for work of an outstanding or fundamental nature in aeronautics.

British Gold Medal for Aeronautics

The British Gold Medal for Aeronautics is awarded for an achievement leading to advancement in aeronautical science.

Simms Gold Medal

The Simms Gold Medal is awarded annually for the best paper read in any year before the Society on any science allied to aeronautics, e.g., meteorology, wireless telegraphy, instruments.

The George Taylor (of Australia) Gold Medal

The Taylor Gold Medal is awarded annually, at the discretion of the Council, for the most valuable paper submitted or read during the previous session.

Wakefield Gold Medal

The Wakefield Gold Medal is awarded annually to the designer of any invention or apparatus tending towards safety in flying, and is open to members or non-members.

Society's Silver Medal

The Society's Silver Medal is awarded, at the discretion of the Council, for some advance in aeronautical design.

British Silver Medal for Aeronautics

The British Silver Medal for Aeronautics is awarded for an achievement leading to advancement in aeronautical science.

Society's Bronze Medal

The Society's Bronze Medal is awarded, at the discretion of the Council, under the same conditions as those for the Silver Medal, but for some less important advance in aeronautical design.

Wilbur Wright Memorial Premium

The Wilbur Wright Memorial Lecture is held annually, a premium of fifty pounds being awarded to the lecturer invited by the Council to deliver the lecture. The lecture is usually given alternately by an American and an Englishman, and is the most important aeronautical lecture of the year. It is delivered whenever possible, on the last Thursday in May of each year.

British Empire Lecture

The Council of the Royal Aeronautical Society have completed the arrangements for the founding of a British Empire Lecture.

The lecture, on any aeronautical subject approved by the Council, will be delivered annually in September in London, by a lecturer, chosen in alternate years from the British Dominions and Colonies and Great Britain.

The Council, by founding this British

Empire Lecture, are anxious to encourage new ideas and new points of view from all parts of the British Empire, and to make the Lecture second only in importance to the Wilbur Wright Memorial Lecture.

The British Empire Lecture will have a premium of £50 attached to it, and in the case of lecturers coming from the Dominions and Colonies an allowance up to £100 will be paid towards the Lecturer's expenses.

It is proposed to hold the first lecture in September, 1945, and suggestions for lecturers should be received by May 31st, 1945, at the latest.

R.38 Memorial Prize

The R.38 Memorial Prize is offered annually for the best paper received by the Society on some subject of a technical nature in the science of aeronautics, preference being given to papers which relate to airships. The prize is twenty-five guineas.

The Herbert Akroyd Stuart Lectures

Under the will of the late Mr. Herbert Akroyd Stuart a sum of £700 is held in trust by the Society for the offer of a prize every two years, for the best paper or lecture read or given before the Society dealing with the Origin and Development of Heavy-oil Aero Engines. The prize is open to members and non-members.

Edward Busk Memorial Prize

The Edward Busk Memorial Prize is offered annually for the best paper received by the Society on some subject of a technical nature in connection with aeroplanes (including seaplanes). Its value is twenty guineas.

Pilcher Memorial Prize

The Pilcher Memorial Prize is offered annually, at the discretion of the Council, for the best paper by a Student on heavier-than-air craft or any analogous subject. Its value is five guineas.

Usborne Prize

The Usborne Prize is offered annually, at the discretion of the Council, for the best paper by a Student on some subject in connection with Aero Engines. Its value is five guineas.

Major Baden-Powell Memorial Prize

The Major Baden-Powell Memorial Prize is awarded in May and December of each year to the student who is considered the best student by the examiners in the Society's Association Fellowship examinations. Its value is three guineas.

Elliott Memorial Prize

The Elliott Memorial Prize is awarded twice yearly to the apprentice at Halton who has the highest percentage of marks in the passing-out examination. Its value is 2½ guineas for each award.

R. P. Alston Memorial Prize

The R. P. Alston Memorial Prize is awarded to any Graduate or Student of the Society for work done leading to improvement in the safety of aircraft, and particularly for improvement in stability and control. Its value is approximately £5.

Branch Prize

The Council offer an annual prize of twenty guineas for the best paper read before the Branches during the previous lecture Session. The prize is open to any member of the Society or of any Branch.

Journal Premium Awards

The Council has set aside an annual sum of £250 to be given as premium awards to authors of papers published in the Journal.

AN APPRECIATION

The Council of the Royal Aeronautical Society wish to thank those Companies who, by their generous co-operation, have done so much to help in the production of the Journal in its new form.

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CONTENTS *APRIL, 1945*

NOTICES .. .. 157—160

THE IMPORTANCE OF POWER UNIT DEVELOPMENT
By Air-Commodore F. R. Banks, O.B.E., F.R.Ae.S. .. 161—213

NOTE ON AIRCRAFT STRUCTURAL FAILURES AND FACTORS FOR SAFETY
By Squadron-Leader J. G. M. Pardoe 214—217

VALUE OF WEIGHT SAVING IN AIR LINERS
By Major F. M. Green .. .. 218—220

THE SOCIETY'S PRIZES .. .. vii—viii

DIRECTORY OF ADVERTISERS xxvi—xxx

The Journal of The Royal Aeronautical Society was founded in 1897 in succession to the Annual Reports. For the opinions expressed in Papers that are signed or initialled the authors alone are responsible. None of the papers or paragraphs must be taken as expressing the opinion of the Council of The Royal Aeronautical Society unless such is definitely stated to be the case. **The Journal is published monthly at the Offices of the Society, 4, Hamilton Place, Piccadilly, London, W.1.** Subscriptions per annum, £4 10 0 post free; Single Numbers 7/6 or 7/9 post free. All communications for publication in the Journal, or on general matters affecting the Society should be addressed to—The Secretary, J. Laurence Pritchard, 4, Hamilton Place, W.1. The Society's Bankers are Messrs. Coutts and Co. All communications respecting Advertisement matters should be addressed to—The Advertisement Manager, Journal of The Royal Aeronautical Society, 4, Hamilton Place, W.1.
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APRIL NOTICES 1945

JOURNAL PREMIUM AWARDS

The Council have set aside an annual sum of £250 for the award of premiums for papers published in the *Journal* and the Council hope that members will contribute papers on their own special subjects.

Graduates' and Students' Section

Monday, 23rd April—Mr. D. L. Brown on "Some Aspects of Aircraft Design." Illustrated by slides and a short film.

Friday, 4th May—Informal Impromptu Discussion. A subject will be announced at the actual meeting. The intention is to enable members to get together for private discussion among themselves.

Both meetings to be held at 7.30 p.m. in the Library at 4 Hamilton Place, W.1.

Wilbur Wright Memorial Lecture

The 33rd Wilbur Wright Memorial Lecture will be read at 6.30 p.m. on Thursday, May 31st, 1945, by Mr. T. P. Wright, Hon.F.R.Ae.S., on "Aviation's Place in Civilisation." The lecture will be held at the Institution of Mechanical Engineers, Storey's Gate, St. James's, S.W.1 (by permission of the Council of the Institution). Light refreshments will be served before the meeting. Visitors will be admitted by ticket, obtainable through Members only.

Honours

The President and Council extend their congratulations to Mr. W. S. Farren, *Fellow*, and Mr. B. N. Wallis, *Fellow*, upon their election to the Fellowship of the Royal Society.

Members of Council

The following is a list of the new Council. Those marked * were elected at the Annual General Meeting held on March 29th, 1945.

President

Sir A. H. Roy Fedden, M.B.E., D.Sc., F.R.Ae.S., M.I.Mech.E., M.I.A.E., M.S.A.E.

Past-Presidents

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*Mr. S. Camm, C.B.E., F.R.Ae.S.
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Mr. C. C. Walker, F.R.Ae.S., A.M.Inst.C.E.

*Mr. B. N. Wallis, C.B.E., F.R.S., B.Sc., R.D.I., F.R.Ae.S., M.Inst.C.E.

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Secretary

Captain J. Laurence Pritchard, Hon.F.R.Ae.S., Hon.M.I.Ae.S.

Branch Lectures

BELFAST BRANCH

Lectures are held in the Central Hall, College of Technology, at 6.30 p.m.

Monday, 16th April—Test Flying, by Mr. J. Lankester Parker, F.R.Ae.S.

BIRMINGHAM BRANCH

Wednesday, 2nd May—Hydraulic Equipment for Aircraft, by Mr. R. H. Bound, F.R.Ae.S.

DERBY BRANCH

The following lecture will be held in the Rolls-Royce Welfare Hall, Nightingale Road, on Monday, May 7th, 1945:—

"Shock Waves at Sonic Speeds," by Dr. W. F. Hilton, B.Sc., A.R.S.C.

GLASGOW BRANCH

Saturday, 21st April—Visit to Prestwick Aerodrome, followed by a lecture by Mr. R. McIntyre, A.F.R.Ae.S.

LUTON BRANCH

Wednesday, 2nd May—The Development of Civil Aircraft, by Mr. N. A. White.

Wednesday, 23rd May—Hydraulics for Aircraft, by Mr. R. H. Bound, F.R.Ae.S.

Wednesday, 6th June—Design and Operation of Deck Landing Aircraft, by Mr. G. E. Petty, F.R.Ae.S.

Fellows

The following were passed by the Council for Fellowship and their elections announced at the Annual General Meeting on March 29th, 1945, in accordance with Rule 4:—

Charles Francis Abell, Arthur Edward Bingham, Robert Boorman, Duncan Cameron, Sir John Adrian Chamier, Herbert Eugene Chaplin, Richard M. Clarkson, Arnold Cadman Clinton, Eric William Densham, Raymond Noel Dorey, Bernard Arthur Duncan, Alan Ferrier, Frederick Arthur Foord, Sir Wilfrid Rhodes Freeman, Henry Herbert Gardner, Charles Henry Griffiths, Stewart Scott-Hall, Arthur Stanley Hartshorn, Edward Dixie Keen, John Henry Larrard, Philip Gadesden Lucas, Sir Francis K. McClean, Peter Gordon Masefield, Albert Basil Miller, Morien Bedford Morgan, Sydney Joseph Nightingale, Robert Bernard Cornelis Noorduyn, Arthur Edgar Woodward-Nutt, Edward Llewellyn Pickles, Douglas Rudolf Pobjoy, Frederick Henry Pollicutt, John Walker Ratcliffe, John Kerr Reid, Harold Rogerson, Fred Rowarth, Norman

Rowbotham, Raymond Harold Sandifer, Arthur Francis Scroggs, John Edward Serby, Beverley Strahan Shenstone, Joseph Smith, Sir Ralph Sorley, Kelvin Tallent Spencer, Herbert Brian Squire, Reginald Spencer Stafford, Andrew Swan, Henry Beaumont Taylor.

Election of Members

The following members were recently elected:—

Associate Fellows

Piotr Bielkowicx, Italo Paul Fatti, Jack Francis (from Graduate), Angus Rayfield Pitt (from Graduate), Jozef Wallis, Ronald Albert John White, Ethelbert Victor Wraight (from Associate).

Associates

Leonard Victor Andrews, Manley John Atkinson, Frederick Baynes, John Beale (from Graduate), James Arthur Brayshaw, Fred Dyson, William Henry Elliott, Gwilym Rhys Evans, John ffitch, Lionel Adrian Basil Hack, Cecil Venn Haines, Charles Ross Haller, John Lawrence Hasler, Albert Holmes Hawes, Ralph Edward Havercroft, Frank Kasz (from Companion), Wilfrid Arnold Parr, George Robert Peel, Douglas Murray Sammon, William Lionel Shippey, Anthony John Sibley, Stanley George Smith, Leslie Twyford, Clifford Uphill, Samuel Winspur, Alister Leslie McCulloch.

Graduates

Reuven Benzwi, Anthony Michael Creedon (from Student), Albert George Mark Elliott (from Student), Francis William Free (from Student), Charles Roger Heaton (from Student), Ernest John Hancock, John Henry, Brian Joseph Howison (from Student), Joseph Kenneth Lance, Harry Lomas, Elton John Perks, Donald Pierce, Alfred Charles William Rattle (from Student), Ernest Frederick Winter.

Students

Henry Gordon Anthony, Denis George Benson, Norman Oliver Brand, Ronald Hugh Chowns, Charles Norman Corn, Peter Robert Davey, Jean Mary Davidson, Anthony Ronald Edwards, David Dunlop Ewart, William Ewing, John Edward Alex Gauld, Sydney Goddard, Roy Thompson Holland, Tudor Llewellyn Jones, John Alfred Laker, Thomas Douglas Lewis, Gerald David Macdonald, Alex Measures, Joseph Merrick, Leonard Gerald Middleton, Oliver Reginald Barton Moorman, Fred Watson Newman, Frederick Arthur Alfred Palmer, Graham Stanley Pool, Philip Hugh Robertson, Reginald Norgate Robilliard, Arthur Edward Rowland, Bryan Leonard Chesterton Smith, Peter Latham Sutcliffe, John Sutton Tatchell, Richard Tourret, John Ashworth Tupman, Edward Wilson Whitley, Ronald Wileman Wilson, Derek John Wood.

Companion

Laurence William Stevens Wilson.

Associate Fellowship Examinations

The Associate Fellowship Examinations will be held on Tuesday, May 15th, and Wednesday, May 16th, 1945. Full particulars will be sent direct to candidates.

Additions to Library

Pamphlets in italics with location reference following in brackets. Books marked * may not be taken out on loan.

A.a.311.—*Le Frottement superficiel en Aérodynamique. F. Haus.* (*Article in "La Science Aérienne," Jan.*, 1940.) *Gauthier-Villars, Paris*, 1940.

B.e.42.—The Model Aeronautical Digest. (Ed. by) R. Copland and R. H. Warring. Model Publications Ltd., Mitcham, 1945. 5/-.

BB.b.113.—*The Engineering Selection of an Airline Aeroplane. John T. Dyment. Engineering Institute of Canada.* (*Preprint, 59th Annual Meeting, 7/2/45.*) (Y.6.i.42.)

BB.f.54.—*Essentials of Meteorology.* (*T.D. Bulletin No. 2.*) *C. H. Klawe. Progress and Engineering Corp., Toronto*, 1944. (Y.14.a.24.) (*Note*: Misleading title—

the article deals exclusively with meteorological *instruments*.)

D.a.B.86 & 87.—*British Air Transport*, (*Cmd.* 6605.) *Minister for Civil Aviation. H.M.S.O.*, 1945. 2*d*. (PD.2.a.16 & 17.) (2 copies.)

D.d.26.—*Engineering Research*. (*A Guide to the Junior Engineer*.) *R. A. Collacott. Crosby Lockwood*, 1945. 1/6. (PE.2.b.19.)

D.d.27.—*Post-War Organisation of Statistics in Government Departments. Institution of Professional Civil Servants*, 1945. (PE.2.b.20.)

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J. Laurence Pritchard,
Secretary.

THE IMPORTANCE OF POWER UNIT DEVELOPMENT

by

Air-Commodore F. R. Banks, O.B.E., F.R.Ae.S.

Air-Commodore F. R. Banks is Director of Engine Development at the Ministry of Aircraft Production, responsible for the development of all piston engines and gas turbines, propellers and engine accessories. In 1930 he joined the Ethyl Export Corporation and was directly responsible for the technical development of leaded fuels used in air and land speed records over many years.

A MEETING of the Society was held in the Lecture Hall of the Institution of Mechanical Engineers, Storey's Gate, St. James's Park, Westminster, London, S.W.1, on Tuesday, February 20th, 1945, at which a paper by Air-Commodore F. R. Banks, O.B.E., F.R.Ae.S., on " The Importance of Power Unit Development," was read and discussed. In the chair, the President, Sir A. H. Roy Fedden.

The CHAIRMAN: Air-Commodore Banks had played an active and important part in engine development during the period between the two world wars. He had filled various positions successfully during the present war at the Air Ministry and the Ministry of Aircraft Production, holding at the moment the key position of Director of Engine Development at M.A.P.

At the beginning of the last war he was serving an engineering apprenticeship; but by juggling with his age he had secured a job in the Royal Naval Reserve on anti-submarine patrol at the tender age of 16 years. Later he was in command of a high-speed surface craft, and at the end of the war had undertaken an unique job of transporting by rail over the Caucasus Mountains six of those boats for the Russian campaign.

Following demobilisation at the end of 1919 he started his peace-time work with some useful Diesel engine development on the north-east coast. But all the time his heart was in aero engines; eventually, about 1924, he started his aero engine career, and he had never looked back. His first job was in connection with the testing of a large airship engine which the British Air Ministry was developing. Later he joined the Anglo-American Oil Company, eventually becoming the technical head of the Ethyl Export Corporation. For a number of years he specialised on aero engine fuels and special fuels for competition work; particularly for the Schneider Trophy aircraft, and in connection with a number of motor car speed trials in America.

Air-Commodore Banks went to America often and maintained close touch with the aviation and fuel technologists there. Indeed, he had a wide background in America, on the Continent of Europe and in this country in connection with the development of special fuels and special engines.

Paper received January 12th, 1945.

" ' The time has come,' the Walrus said,
' To talk of many things :
Of shoes—and ships—and sealing-wax—
Of cabbages—and kings—
And why the sea is boiling hot—
And whether pigs have wings.' "

I HAVE quoted from Lewis Carroll's famous work because it fits my paper. Unfortunately, however, I cannot speak in detail, or even mention, some of the many things happening in the engine world at this moment. But I am going to attempt to give you my picture of the future of the aviation power unit.

My title stresses the importance of development and indeed, this cannot be overstressed. It may be thought that I have wandered somewhat from my title early in the paper. This is not so, since all that I mention cannot be effected without the most intensive development.

I have been engaged on engine development for some years and have definite views on the subject.

We have seen great things in the development of the piston-type aero engine during the last twenty-five years or so; and nowhere have these developments been greater than in this country.

We have witnessed the evolution of the sleeve valve, which became a practical proposition in this period; despite the fact that its inventors—Burt and McCullum—thought of it long before the last war. There have been many other developments, such as the sodium cooled valve, lead bronze and silver lead bearings, variable pitch and constant speed propellers, the supercharger and, last, but not least, the development of fuels of high anti-knock value and better lubricants.

All these and other things, coupled with improved designing technique and long experience, helped also by the urgency of war, have combined to give us engines of very high power output for relatively low weight and moderate cylinder capacity.

But the materials people have probably contributed as much as anyone else to the excellence of our present engines.

One engine has doubled its maximum power in the last eight years or so—from 31 B.H.P. per litre or 3.1 B.H.P. per sq. in. of piston area to 63 B.H.P. per litre or 6.2 B.H.P. per sq. in. of piston area. And its supercharged height has been more than doubled. While it is now operating at this specific power in service, it has already been further developed to give very appreciably more power.

All this has been most encouraging and reflects great credit on the aero engine industry. But now we are about to see a change; a change in the type of power unit and one which will influence aviation much as the advent of the steam turbine revolutionized ship propulsion and the size of power stations.

I refer, of course, to the gas turbine, which has come to stay and will eventually usurp the well-earned place of the piston engine. The influence of the gas turbine is already felt and in a few years it will be commonplace. It will, I believe, be used for forms of transport other than aircraft and particularly for marine purposes.

Whittle can rightly be regarded as the " Charles Parsons " of the aviation power unit. And it is rarely in a lifetime that an entirely new and really practicable prime mover is evolved.

I would like these words borne in mind throughout the reading of the paper; because, although I feel that the piston engine has some years still to go in aviation, its principal claim for remaining will be its cruising fuel consumption, particularly at altitudes below, say, 20,000 feet.

Speed, or a high rate of development, is essential in the aero engine field. Development should be systematically done, even although there are times when commonsense appears to fail and one has to resort to some extreme in order to get a line on the next step to take and to reorientate one's ideas.

Speed, in development, is important for another reason, that is, the time taken to get an engine into production from (and

including) the drawing board stage. Experience has shown that this is somewhere between four and five years. And during this time prototype engines have to be built and flown, because it is only by flying that one can get down to all the troubles. There are indications now, however, that the period might be cut somewhat where engines of similar cylinder arrangement are concerned and as the result of long experience. One engine comes to my mind which has been developed and got into production in little over three years.

Due to this time factor there are, usually, improved versions of the engine coming along in the experimental shop before the original is in full production. And a good basic type engine will have many "Marks" before it becomes obsolete.

This is where Design comes into the picture—original Design. A successful engine is one so designed that it has plenty of development inherent in it and its performance can be improved in attractive steps over an appreciable period—say, seven or eight years —without radical re-design.

It is a costly process, in time and money, to design an engine which is so restricted that a major re-hash is necessary before a real improvement in performance can be obtained.

The aircraft manufacturer must be considered, too. It is much to his and everybody's advantage if he can have an engine which promises forward development with minimum external change in shape and size. This is particularly important in war, where it is absolutely necessary to get the best from a given aircraft and meet new or changing operational demands without having to resort to a completely new aircraft type with its resultant cost in development and production time.

I could wish, however, that more appreciation were shown of the efforts which the engine manufacturer has made to improve the performance of his engine; often to be wasted by inattention to detail design of the airframe which, in the form of " drag," absorbs a large proportion of the increase in engine power. " Dragging " some aircraft through the air is (almost) literally true.

Some are, at last, becoming more conscious of the need for minute attention to detail in this respect, particularly with speeds approaching 500 m.p.h.; and already above this figure in some cases.

As a matter of fact, it is now, practically, thrust upon the aircraft designer and manufacturer to produce a clean airframe for these speeds because, if they do not do so, small inaccuracies and bad detail work may make the machine unsafe to fly.

It is most important to strike the correct balance between design and development. In the past many engines have been " built first and designed afterwards." By this I mean that a good deal was left to the development department to settle by their testing.

Whilst this method has produced results—often very good results—I do not think it the best way of doing things. Sound engineering design is essential and if it is not present the development department has to " cut and try " to excess, and this means unnecessary work and delay. The production people also come into the picture, to give guidance to the design staff and so avoid machining processes which are unnecessarily complicated and costly.

AS WITH PRODUCTION, "TIMING" IS ESSENTIAL IN ALL DEVELOPMENT WORK. A STRICT TIME-TABLE SHOULD BE ADHERED TO FOR THE DEVELOPMENT PROGRAMME AND THE VARIOUS PROJECTS AND ITEMS PROGRESSED IN THE NORMAL WAY AND BY WEEKLY MEETINGS, ATTENDED BY ALL CONCERNED.

The foregoing will seem rather obvious to some of you, but I have had personal experience where firms have taken a long time to build their prototype engines because they would not issue anything but the most com-

plete drawings to the experimental shops and ones which were, virtually, expected to be the final production standard for the engine. There is still a lot to learn about engines, particularly in the case of the modern engine of high specific power output; and it is not possible to evolve a design which will not be altered in many respects, if only in details, before the engine is ready for production.

The firm having the best development department will win every time, even if its competitors have good designing technique. But, obviously, the ideal is to have good design technique coupled with efficient development. And efficient development, in any case, will make for superior designing technique because it gives the designer the information he requires.

Many engines of promising design have failed to see the light of day because their development has been poor. And the designer had insufficient data to design out of his troubles.

To sum up, a successful aero engine is a " combined operations " job, necessitating complete co-ordination between the Design, Development and Production staffs.

The Shape of Engines to Come

I would like now to give my personal views on forward engine types.

I am doubtful whether we shall see the reciprocating engine in unit sizes above 6,000 b.h.p., or even as big. Whilst it is possible to build engines of this, or higher, power, it does not seem to me to be worth while, particularly in view of the problems associated with their installation and their propellers. Further, after talks with various aircraft people, it appears that they would prefer not less than four engines and might consider even more for very large machines.

There have been many arguments—and there still are for that matter—on the shape of an engine and whether it should be air- or liquid-cooled; poppet or sleeve valve; radial or in-line, etc., etc. But I think we can see more clearly on these matters to-day and can, therefore, be more definite in our choice.

Here are some points for consideration before deciding upon the final shape :

(a) There is little difference between the installed weights of air- and liquid-cooled engines, power for power. In some cases the air-cooled installation is even slightly up in weight compared with the liquid-cooled job.

(b) Both poppet and sleeve valves work satisfactorily. The poppet is susceptible to " lead " attack. But, I submit, it makes for a somewhat lighter engine and the piston temperatures are lower than those of a sleeve valve engine. The sleeve valve allows neater arrangement and better geometrical layout. It is not materially affected by lead. But it does not give superior volumetric efficiency compared with the poppet valve.

A number of claims have been made for the sleeve valve engine which have not, to date, been substantiated. For instance, it is said that its maintenance is less. But the modern poppet valve engine does not need more attention than the sleeve type, over equal operating periods and before servicing is necessary. It is usually the piston or ring gumming condition which sets a limit to the hours run between overhaul. And the sleeve valve is not yet superior in this respect. But the relative immunity of the sleeve from " lead " attack makes it attractive. In my opinion, all future high duty sleeve valve engines should start with direct piston cooling because of their higher piston temperatures.

In regard to the question of air- or liquid-cooling; this, I think, is now more a matter of personal preference rather than technical consideration—with the proviso that the air-cooled engine will not, in my opinion, attain the high specific power output of the liquid-cooled job. The latter has,

what might be termed, a better "heat capacity factor."

Again, in the case of the liquid-cooled engine, it can be made in a more compact form and the cylinder block contributes, or should contribute, to the total stiffness of the engine. The in-line air-cooled engine is longer and less compact because of the cooling fins, which control the pitching of the cylinders and because of the baffles, which take up more space and do not lend themselves to such neat arrangement as the jackets of a liquid-cooled engine. The crankcase must also be somewhat heavier to ensure the necessary stiffness; to which the cylinders, because of their separate mounting, cannot contribute.

Coming now to the actual shape of the engine: I favour the in-line engine, whether it is to be air-cooled or liquid-cooled.

Since "power per sq. inch of piston area" is the criterion of engine performance—assuming similar piston speed—it is particularly necessary, in the big powers, to cram in as large a piston area as possible. And this can only be done by arranging the cylinders in 'H' form (usually on its side), with two crankshafts; or in radial form, either as an 'X' or as a multi-cylinder radial—viewed from the front. I think the aim should be to keep as few cylinders as possible per crankpin, but, since the six cylinder crank appears to be the optimum as regards length and stiffness, there is little alternative to the arrangement quoted, particularly if a reasonable cylinder size—up to 6in. diameter—is kept.

The staggered two-row radial of high power has been a very successful type, but its further development presents a considerable problem in dealing with balancing and vibration, and it is difficult to make a really smooth engine. It also promotes high propeller blade stresses. And its cooling is not easy, even although we are now learning how to do this better.

All in all, if one decided upon an air-cooled engine, I think the 24 cylinder 90° 'X' type with four banks of six cylinders in-line, is the best arrangement. And it allows plenty of space between the cylinders for the cooling air and for the proper arrangement of the induction and exhaust systems. The induction and exhaust systems of the modern engine play such a large part in its over-all efficiency of operation that it is (almost) true to say that the best way of designing an engine is first to design the induction and exhaust systems and fit the cylinders in where you can!

The 'X' arrangement—assuming cylinder bores of 5½in. or 6in.—may be criticised because, keeping to 24 cylinders, a limitation in the total power output of the engine will be imposed. But, here again, one wonders whether it is worth going above 3,000 b.h.p. for the air-cooled engine, because it may become much heavier than its liquid-cooled counterpart, for the reasons I have mentioned previously. One can, of course, go to the 28 cylinder arrangement with four banks of seven cylinders radial; but this means an increase in the number of cylinders per crankpin and may impose further limitations because of the greater masses involved. Also, the reduction of space between the cylinder banks tends to cramp the induction and exhaust systems and, also, the air passages.

We might be able to go to bigger cylinders—above 6in. bore—and there are indications that the sleeve valve may not be so limited as the poppet in regard to increasing cylinder size, in which case an engine with large cylinders, limited to 24 in number, is feasible.

In the case of liquid-cooled engines, one would suggest that up to about 2,500 b.h.p. and, possibly, 3,000 b.h.p., the classic 12-cylinder 60° 'V' cylinder arrangement is the best from all points of view. But, from 3,000 b.h.p. and upwards, some other cylinder arrangement is necessary.

I do not think it necessary to go beyond 24-cylinders for liquid-cooled engines up to

6,000 b.h.p. and the decision rests between the 'X' and 'H' arrangements.

The 90° 'X' for the liquid-cooled engine makes for a rather unnecessarily big cowling circle, whereas the horizontal 'H' engine can be more neatly installed. And the latter has the advantage of only two cylinders per crankpin, although one is committed to two crankshafts.

I have been thinking of a narrow 'X' arrangement, horizontally disposed, thus ><; the angle between adjacent cylinder banks being 60° or less. Whether or not the (heavier) single crankshaft, together with four cylinders per crankpin, would be any lighter overall than the two crank 'H' arrangement, is a matter for analysis.

In all the cases cited here I assume a piston speed of 3,250 ft. per minute.

Radiators and Oil Coolers

Whilst the problem of cooling the air-cooled engine is difficult, that of finding adequate radiator space for the liquid-cooled engine is also becoming more difficult with increasing power.

But whereas the air-cooled engine has to have all its cooling adjuncts attached directly to it and strictly in relation to its cylinders, the liquid-cooled engine allows more latitude in regard to radiator position, which can be at any one of several points in the airframe.

Radiator and oil cooler technique, from the point of view of design, manufacture and inspection, has been very crude. And the radiator matrix was expected to stand stresses (of installation and vibration), which were not part of its functions and under which it failed badly.

Improvements in these respects are now in hand, but I would like to see some unconventional and bright ideas from the engine people, on coolers generally. It might be a good thing to give the job of designing a new cooling system to someone who has never seen a radiator or oil cooler before, but who has very sound thermodynamic and mechanical engineering experience.

Transport Engines

There seems to be a feeling in some quarters that engines for transport aircraft should be designed particularly for the purpose and be of conservative power rating.

I do not hold with these views and, in fact, feel most strongly that, if such were the case, we should get heavy engines and power plants, the further development of which would be very limited.

There is no better way of obtaining a light high duty engine of reliable performance than by designing and developing it along military lines.

Military engine types can be adapted and modified for transport operation, and these are the lines upon which we, in this country, are proceeding.

If the engine is so developed to give high take-off power it will probably be able to cruise continuously at 35 per cent. to 40 per cent. of this power. If, however, an engine were designed along the lines suggested by some, we would get mediocre performance and inferior maximum or take-off power, which would mean the engine having to cruise at a higher percentage of its take-off power—say, 50 per cent. instead of 40 per cent.

We are aiming to obtain, eventually, 1,000 hours between overhaul and servicing periods. This may take another year or more to achieve, but it will be done.

Whilst a running period of 1,000 hours will be most satisfactory, we hope to get 600-700 hours operation very shortly.

We should not, however, go blindly on and expect to get trouble-free operation beyond this maximum period (of 1,000 hours) for some time to come. The engine must work efficiently throughout its running time, and there is a risk that if a longer period is attempted it will restrict the development of the engine in other directions. After all, the difference between, say, 700 hours and 1,000 hours may only mean one more servicing period in a year's flying or about four overhauls to three. But what we require is

complete reliability during the running period. This also applies equally to the proprietary accessories fitted to the engine, including the sparking plugs, the propeller, and its ancillary equipment. None of these items should require any attention over the engine operating period.

We must also make absolutely clean engines and propellers; completely free from oil leaks, etc.

I did ask some time ago that engines should be painted white in order to show up oil leaks, but it was found that to obtain a pure white surface meant about three coats of paint or enamel and this in itself stopped up important leaks. We are now trying out a medium shade of grey paint and some of the airline companies have asked for no finish on the outside of the engine at all, except that the main part of the engine, such as the cylinder block (in the case of a liquid-cooled engine) and crankcase, be " scratch-brushed."

I think a good deal of attention will have to be paid to the exhaust system in order to obtain durability and safety.

I am hoping that the final development of the piston type transport engine will be able to give us a specific fuel consumption of 0.40 lb. per b.h.p. hour and even 0.38 lb. per b.h.p. hour, in about five years' time.

Fuel and Fuel Economy

At the present moment 100-130 grade fuel is in general use for military purposes by the Allied Air Forces throughout the world. Fuels of higher rating, or grade, are under consideration and, although we would like to see a fuel conforming to, say, 130-160 grade, I doubt whether such a fuel could be available for a long time to come because of production restrictions.

Before going further, it might be as well to explain what this fuel grading method means in assessing anti-knock value.

The C.F.R. Motor Method test was evolved some years ago and evaluates fuel quality in terms of octane number. This is a laboratory test which measures the anti-knock value of any particular fuel in terms of the percentage of pure iso-octane in a blend of iso-octane and normal heptane. The test is made under conditions of maximum knock mixture strength—weak mixture conditions. But although the octane number scale under these test conditions is reasonably satisfactory up to 100 octane number, it does not give any idea of anti-knock value beyond 100 octane.

The octane scale has been in constant use for some years, but it became evident, in testing and developing aviation fuel, that fuels having different compositions but the same octane number, behaved differently in the engine throughout the mixture range. For instance, two fuels, one containing a large proportion of aromatics and the other a very small proportion, might have the same C.F.R. Motor Method rating, but would, under take-off conditions in a full-scale engine, give completely different answers in terms of power output before detonation set in.

As a result of this, it was realised that fuels should not only be assessed in terms of their weak mixture quality, but also given a certain take-off performance rating under rich mixture conditions.

From about 1936 onwards we, in this country, used full-scale single cylinder aero engine units to determine the take-off performance of our fuels. And, in the early days of the war we called for a certain minimum quality in this respect, although at that time the specification as such merely asked for a 100 octane number " Motor Method " fuel.

When America entered the war they also felt the need for improved combat and take-off ratings for their engines and the joint need for satisfying this (take-off) quality of the fuel was firmly established and a laboratory test method developed to corre-

late the results obtained on both full scale multi- and single-cylinder engines.

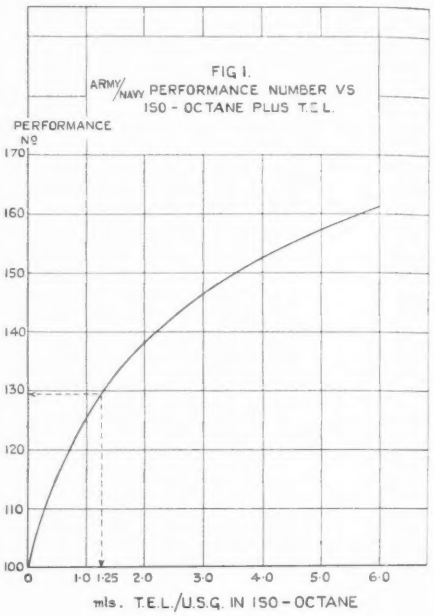
This became known as the C.F.R./A.F.D.3C test method and called for the rating of fuels under rich mixture conditions in terms of a reference fuel scale.

Since iso-octane was regarded as the primary reference fuel for determining anti-knock properties, the use of iso-octane, plus tetra ethyl lead, was agreed as the reference fuel scale. The rich mixture quality of a fuel was determined by matching a blend of iso-octane plus T.E.L. against it under the established test conditions. The rich mixture quality of the then current 100 octane fuel was specified as being equal to S (commercial iso-octane of high purity), plus 1.25 ccs of T.E.L. per American gallon.

But rating fuels in terms of S plus lead is not entirely satisfactory since the response of different fuels to a given amount of lead (the lead response curve) varies from one engine to another and the aero engine manufacturer was not able to predict the performance of his engine by ratings of fuels quoted to him in terms of the reference fuel scale. Therefore, some "performance" scale was necessary to enable him to assess the likely behaviour of the various fuels in his engine.

This scale was evolved by plotting a curve giving, on the one hand, the performance, on an I.M.E.P. basis, of the test fuels, relative to iso-octane and, on the other, the iso-octane plus T.E.L. ratings of the same fuels. In view of the large number of engine types and testing stations involved, the results when plotted showed a fair amount of spread, but a mean curve was drawn through all the points and from that curve a table was made showing the "performance number" equivalent to any particular S plus T.E.L. rating. (See Fig. 1.)

From this performance scale the rating of iso-octane plus 1.25 ccs T.E.L./American gallon (equivalent to 100 octane fuel) is about 129.5. For the purpose of specification this was rounded off at 130; and the current 100 octane fuel then became known as 100-130 grade—100 under the "Motor Method" or weak mixture condition and 130 for the rich mixture condition.



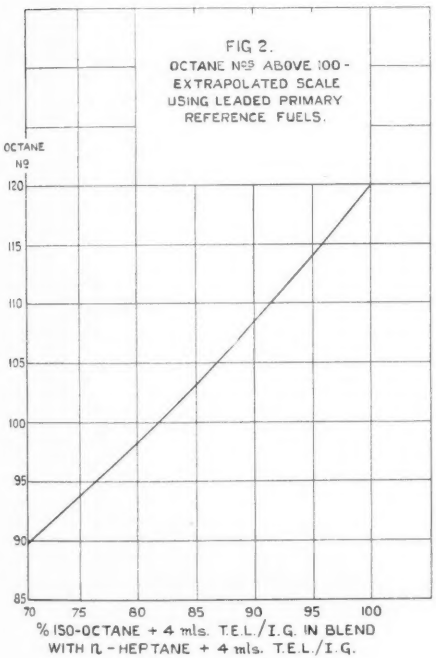
The performance scale suffers from the fact that it is based upon iso-octane plus T.E.L.; since the addition of equal amounts of T.E.L. in a fuel does not give the same increase in performance, *e.g.*, if a performance number of 100 is assumed to be equivalent to iso-octane without T.E.L., the performance number of iso-octane plus 1 cc T.E.L. is about 125, plus 2 ccs is 138, plus 3 ccs 147, plus 4 ccs 153, and plus 5 ccs 157.5. The scale then becomes so close that it is not of much use above this figure, in assessing rich mixture anti-knock quality.

So far we have considered the anti-knock quality (weak mixture condition) of the fuel up to 100 octane and its particular rich mixture rating, but it is equally important to be

able to assess the weak mixture value above 100 octane. In this country we have been working in terms of "extrapolated octane numbers" by adding lead to both iso-octane and normal heptane, in an arbitrary concentration of 4 ccs of T.E.L. per Imperial Gallon, thus raising and re-rating the normal octane scale and extrapolating it to obtain weak mixture values above 100 octane. (See Fig. 2.)

But, in America, the iso-octane plus T.E.L. scale is used to measure weak mixture quality above 100-octane as well as for measuring rich mixture anti-knock quality.

The Americans have recently taken the additional step of using the performance



scale derived for *rich* mixture quality and applying it to give an expression of the weak mixture performance of the fuel. Thus, when they think of a fuel of weak mixture quality equal to, say, S plus 0.50 cc T.E.L. per American gallon, they quote the figure 115 (see Fig. 1) as the weak mixture performance number. This then leads to the expression of anti-knock values better than 100 octane number and better than 130 grade, such as 120-150, or, as I mentioned at the beginning of this section, 130-160.

We have retained the C.F.R. Motor Method whereas the Americans have developed the A.F.D. 1C test method, which makes use of the same basic laboratory engine, but has a different method of detecting detonation—by temperature plug.

We have tried fuel of 100-150 grade with considerable success, but although it helps us from the point of view of maximum power, it offers no improvement to the cruising rating of the engine.

For transport, as distinct from military purposes, we must consider 100-130 grade as the fuel at present available for developing our transport engines.

We have been doing a considerable amount of work lately on the distribution of fuel to the individual cylinders of the engine and some rather startling and disturbing facts have come to light. Not only have we found—what was already known—that some cylinders received the bulk of the "heavy ends" of the fuel and the others the "lighter ends," but, also, the lead in the fuel is similarly distributed and follows the "heavy ends"; since tetra-ethyl lead has a boiling point nearer the "heavy ends," although somewhat above them (200° C.). The ethylene di-bromide having a lower boiling point (131°C.) follows the lighter ends, with the result that the cylinders receiving the heavy ends and the high concentrations of lead show very heavy lead deposit because there is too little bromine compound to convert it to volatile form.

I cannot impress upon those concerned too strongly that good distribution is absolutely essential. If some cylinders are not receiving the correct amount of lead it is a sheer waste of high knock rating fuel or, in

late the results obtained on both full scale multi- and single-cylinder engines.

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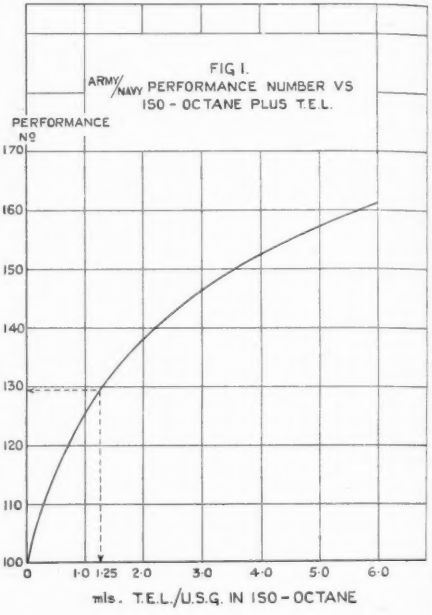
Since iso-octane was regarded as the primary reference fuel for determining anti-knock properties, the use of iso-octane, plus tetra ethyl lead, was agreed as the reference fuel scale. The rich mixture quality of a fuel was determined by matching a blend of iso-octane plus T.E.L. against it under the established test conditions. The rich mixture quality of the then current 100 octane fuel was specified as being equal to S (commercial iso-octane of high purity), plus 1.25 ccs of T.E.L. per American gallon.

But rating fuels in terms of S plus lead is not entirely satisfactory since the response of different fuels to a given amount of lead (the lead response curve) varies from one engine to another and the aero engine manufacturer was not able to predict the performance of his engine by ratings of fuels quoted to him in terms of the reference fuel scale. Therefore, some "performance" scale was necessary to enable him to assess the likely behaviour of the various fuels in his engine.

This scale was evolved by plotting a curve giving, on the one hand, the performance, on an I.M.E.P. basis, of the test fuels, relative to iso-octane and, on the other, the iso-octane plus T.E.L. ratings of the same fuels. In view of the large number of engine types and testing stations involved, the results when plotted showed a fair amount of spread, but a mean curve was drawn through all the points and from that curve a table was made showing the "performance number" equivalent to any particular S plus T.E.L. rating. (See Fig. 1.)

From this performance scale the rating of iso-octane plus 1.25 ccs T.E.L./American gallon (equivalent to 100 octane fuel) is about 129.5. For the purpose of specification this was rounded off at 130; and the current 100 octane fuel then became known as 100-130 grade—100 under the "Motor Method" or weak mixture condition and 130 for the rich mixture condition.



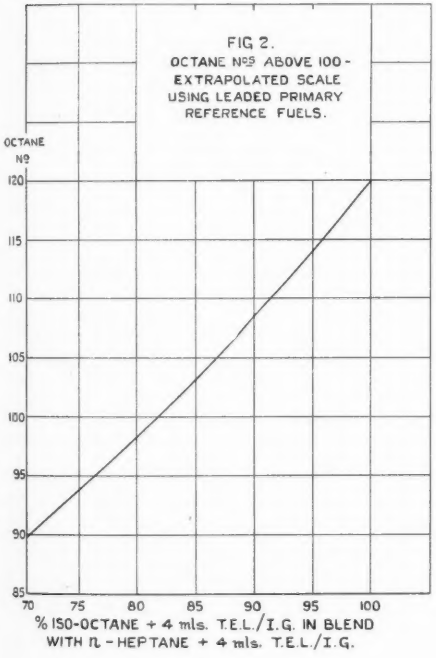
The performance scale suffers from the fact that it is based upon iso-octane plus T.E.L.; since the addition of equal amounts of T.E.L. in a fuel does not give the same increase in performance, *e.g.*, if a performance number of 100 is assumed to be equivalent to iso-octane without T.E.L., the performance number of iso-octane plus 1 cc T.E.L. is about 125, plus 2 ccs is 138, plus 3 ccs 147, plus 4 ccs 153, and plus 5 ccs 157.5. The scale then becomes so close that it is not of much use above this figure, in assessing rich mixture anti-knock quality.

So far we have considered the anti-knock quality (weak mixture condition) of the fuel up to 100 octane and its particular rich mixture rating, but it is equally important to be

able to assess the weak mixture value above 100 octane. In this country we have been working in terms of "extrapolated octane numbers" by adding lead to both iso-octane and normal heptane, in an arbitrary concentration of 4 ccs of T.E.L. per Imperial Gallon, thus raising and re-rating the normal octane scale and extrapolating it to obtain weak mixture values above 100 octane. (See Fig. 2.)

But, in America, the iso-octane plus T.E.L. scale is used to measure weak mixture quality above 100-octane as well as for measuring rich mixture anti-knock quality.

The Americans have recently taken the additional step of using the performance



scale derived for *rich* mixture quality and applying it to give an expression of the weak mixture performance of the fuel. Thus, when they think of a fuel of weak mixture quality equal to, say, S plus 0.50 cc T.E.L. per American gallon, they quote the figure 115 (see Fig. 1) as the weak mixture performance number. This then leads to the expression of anti-knock values better than 100 octane number and better than 130 grade, such as 120-150, or, as I mentioned at the beginning of this section, 130-160.

We have retained the C.F.R. Motor Method whereas the Americans have developed the A.F.D. 1C test method, which makes use of the same basic laboratory engine, but has a different method of detecting detonation—by temperature plug.

We have tried fuel of 100-150 grade with considerable success, but although it helps us from the point of view of maximum power, it offers no improvement to the cruising rating of the engine.

For transport, as distinct from military purposes, we must consider 100-130 grade as the fuel at present available for developing our transport engines.

We have been doing a considerable amount of work lately on the distribution of fuel to the individual cylinders of the engine and some rather startling and disturbing facts have come to light. Not only have we found—what was already known—that some cylinders received the bulk of the "heavy ends" of the fuel and the others the "lighter ends," but, also, the lead in the fuel is similarly distributed and follows the "heavy ends"; since tetra-ethyl lead has a boiling point nearer the "heavy ends," although somewhat above them (200° C.). The ethylene di-bromide having a lower boiling point (131°C.) follows the lighter ends, with the result that the cylinders receiving the heavy ends and the high concentrations of lead show very heavy lead deposit because there is too little bromine compound to convert it to volatile form.

I cannot impress upon those concerned too strongly that good distribution is absolutely essential. If some cylinders are not receiving the correct amount of lead it is a sheer waste of high knock rating fuel or, in

popular, if incorrect parlance, "octane number." In other words, the cylinders receiving a lead concentration below the average in the fuel are restricted in power, but with perfect distribution the engine would give the same power on much lower quality fuel and 100 octane fuel would not, for that power, be necessary.

Tests have been done on 100-130 grade containing 7.2 ccs lead per imperial gallon where analysis of the exhaust gases showed that some cylinders were receiving a lead concentration equivalent to the 12 ccs per gallon; and, in some cases, even more!

A V type 12-cylinder engine was used for these tests and, under running conditions which caused sparking plug fouling in service, the T.E.L. contents of the fuel going to the individual cylinders were as follows. On the left cylinder bank, No. 1 cylinder received 4.9 ccs/I.G.; No. 2 5.3 ccs; No. 3 5.3 ccs; No. 4 5.0 ccs; No. 5 6.3 ccs; No. 6 5.2 ccs.

On the right bank, No. 1 cylinder received 12.1 ccs T.E.L./I.G.; No. 2 9.8 ccs; No. 3 10.2 ccs; No. 4 6.3 ccs; No. 5 6.6 ccs; No. 6 6.7 ccs.

Nos. 1, 2 and 3 cylinders on the right bank not only received a large amount of lead but, in view of the equitable distribution of ethylene di-bromide, they received the lead in the form of approximately 0.5 T mix of ethyl fluid, or only about half of the ethylene di-bromide required to combine with the lead. Furthermore, the octane number of the fuel delivered to No. 2 cylinder on the left bank was only about 95, whereas that delivered to No. 1 cylinder on the right bank is better than 103 octane number.

The rich mixture quality of this fuel is equivalent to 120 performance number so it might be said that the worse cylinder, which after all determines the performance of the engine, is operating on 95-120 grade fuel, whereas the fuel in the tank is 100-130 grade.

When one realises the tremendous pressure which has been exerted throughout the war to relax the weak mixture quality even by one octane number in order to improve production, it will be seen that if a fuel of this lower quality could have been used satisfactorily the production position would have been happy indeed.

To improve distribution I feel that we must eventually go to individual injection to each cylinder—either directly into the cylinder, or injecting through the inlet ports. This is, I submit, particularly necessary in the case of large engines. But if this is done the question of air distribution to the cylinders must not be forgotten, because it is not necessarily the case that the air is equally distributed.

Timed or individual injection means that there will be some loss in blower efficiency and that the blower will have a reduced compression ratio. But this mainly affects the maximum power condition and can be overcome by water or water/methanol injection in the eye of the blower for take-off and/or combat conditions.

Whilst distribution has an effect on fuel economy, both as regards making full use of the anti-knock value of the fuel and reducing consumption, it does not have a profound effect on consumption as a whole; and the question of fuel consumption is going to be very important in the future, particularly for air transport machines and long range bombers. Whatever one does to improve the distribution to the individual cylinders, the resultant reduction in fuel consumption will still be insufficient and we must look elsewhere to obtain a real improvement in consumption.

To obtain the best conditions for minimum fuel consumption, the engine must have a high mechanical efficiency and take as much energy from the fuel as possible. This means that under cruising conditions the engine will run at the lowest speed (r.p.m.) practicable

and with the highest M.E.P. possible. I can foresee no real gain in increasing the compression ratio above 7-1 since such an increase results in high peak combustion pressures and will restrict the boost which can be used for full power and take-off.

The only way to obtain a real improvement in fuel consumption is to utilise the energy of the exhaust gases, either by means of a turbo blower, or a turbo driving back to the crankshaft through gearing.

It is said that the relatively simple ejector exhaust pipe will make as good use of the exhaust gases as the turbo blower, when the aircraft is cruising above 350 m.p.h., or thereabouts. I feel, however, that the turbo blower will still be effective at these speeds. But one will have to make a balance sheet to see whether or not the weight of the turbo blower and the more complicated exhaust system and ducting does not militate against increased power by adding undue weight and " drag " to the aircraft.

Safety Fuels

The development of individual injection to each cylinder opens the way to the use of so-called safety fuels. These are high flash point (100°F.) fuels having much the same anti-knock properties as aviation petrols now in use.

The question of how safe these fuels are is still very largely undetermined. From the point of view of safety fuels in military aircraft, explosive fuel/air mixtures will exist in the fuel tanks over a much wider range of conditions than is the case with high volatility aviation fuels. But the effect of safety fuels upon fires in crashes has yet to be determined.

One would expect that since direct injection involves merely boosted air in the induction system, rather than a boosted fuel/air mixture, then the boosted mixture fire consequent upon engine failure will disappear and, certainly, since the vapour pressure of the fuels will be very much lower than those now current, the dangerous area surrounding fuel tanks after crash should not be so large and the chances of flash back to the fuel from relatively distant fires much more remote.

A further point of importance, both in military and civil operations, is that the very low vapour pressure will reduce, to vanishing point, the loss of fuel due to evaporation in flight.

A good deal of work still remains to be done to evaluate the future possible use of fuels of this type, but they certainly merit detailed and practical investigation.

The Gas Turbine

THE GAS TURBINE HAS NOT ONLY COME TO STAY, BUT IT IS BOUND TO TAKE THE PLACE OF THE PISTON ENGINE FOR MANY APPLICATIONS. IT WILL, IN MY OPINION, BE SO COMPETITIVE IN FIVE OR TEN YEARS' TIME THAT THE LARGE PISTON ENGINE MAY NOT SURVIVE. AND THE SMALLER PISTON ENGINE WILL HAVE A HARD TIME TO EXIST, ALSO.

The principal disadvantage of the gas turbine is its high fuel consumption. For this reason alone the piston engine will remain in the picture for some time and until we know more about the operating economy of the gas turbine and the particular design of aircraft required for it.

But one great advantage of the gas turbine is the speed at which it can be evolved. It takes about one-third of the time to design and build a prototype turbine of the simple " jet " type, compared with a piston engine of comparable power. Even the more complex turbine types and those having propellers should only take about half the time of the equivalent piston engine, to build.

For instance, a piston engine will take some eighteen months from the design to the prototype stage, and then another two to three years to the commencement of production.

Whereas the simple turbine/jet takes about six months to design and build in prototype form and, approximately, a further year to put into production—eighteen months in all as opposed to four years or so for the piston engine.

Further, the simple turbine/jet is about one-third of the weight of the piston engine—power for power—and its installed weight is little more than its " dry " weight; because it does not have a radiator or coolant, neither is a large quantity of lubricating oil necessary for its operation. Nor is an oil cooler required when ball or roller bearings are used instead of plain bearings.

The smoothness of operation of the gas turbine, whether used in " jet " form or with a propeller, is such that the airframe will undoubtedly need less maintenance than is at present required for those aircraft fitted with the high duty piston engine and where, in consequence, there is considerable vibration.

The gas turbine can be built in a number of different forms. One is the original and classic " Whittle " type, having a single stage centrifugal blower and single stage turbine and operating as a pure " jet." Another form, working on similar principles, is that using a multi-stage axial blower with a turbine wheel. Both these types—centrifugal and axial—can be arranged to drive a propeller, through double reduction gearing, by suitable proportioning of the blower to turbine.

There are also turbine/propeller combinations using axial and centrifugal blowers in series, in order to give a higher pressure ratio and improved economy. Other blower and " staging " arrangements are possible.

There is also the turbine with augmenter. This is really a turbine type fan in an annular duct surrounding the main turbine. The fan is usually connected to a ring of turbine blades located in the gas stream of the turbine proper. This augments, or supplements, the main jet stream and is, virtually, a " half-way house " between the simple jet and the turbine-driven propeller.

These various combinations will be tried in the near future and we will then know something of their relative merits. But a good deal of intelligent guessing and calculation is in progress at the present time in an endeavour to forecast the best arrangement for a given aircraft requirement.

The basic difference between the turbine/jet and turbine/propeller arrangement is that the simple jet gives all its available power in the form of exhaust jet energy; the exhaust gas being ejected as a relatively small diameter high velocity stream (about 1,600 ft. per second), the reaction of which propels the aircraft through the air. Whereas the turbine/propeller arrangement uses about 80 per cent. of the turbine available power to drive a normal propeller and the remainder is employed in " jet " form. The propeller can be considered as a large diameter low velocity unducted fan.

The figure of 80 per cent. is chosen arbitrarily to illustrate this case, but the division of power as between the propeller and the jet can be so arranged to suit any particular operating condition.

In the case of both the turbine/jet and turbine/propeller their propulsive effect is highest when there is least difference in speed between their respective " discharges " and the speed of the aircraft in which they are fitted.

This assumes that efficiency is assessed on a change of kinetic energy basis; where input per lb. of air flow is equal to the jet kinetic energy less the kinetic energy of forward speed—

$$\frac{Vj^2}{2g} - \frac{V^2}{2g}$$

It is difficult to estimate what the operating economy of a gas turbine will be, in the air, from the fuel consumption obtained on the test bed; since at altitude it is run at conditions (higher $n/\sqrt{t}$ values) which cannot yet be exactly simulated on the test bed at

sea level and " static " conditions. But this difficulty (which is similar to that of the modern piston engine having a carburettor or injection system with automatic adjustment and compensation) will eventually be overcome when we are able to test the blower and turbine, separately or combined, in special altitude test houses.

The relatively high test bed fuel consumption of the simple turbine/jet is generally improved upon in the air, particularly at high altitude, say, 36,000 ft. The reason is that—assuming constant speed (r.p.m.) conditions—the combustion temperature, or the temperature of the gases at the turbine entry, together with the temperature rise across the blower, will remain approximately constant. Therefore, since the ambient temperature is lower at altitude, there will be a higher temperature ratio across the engine and a higher pressure ratio across the blower. These effects may, however, be somewhat offset by a drop in adiabatic efficiency and the " slip " factor of the blower.

In the case of the simple turbine/jet a reasonable fuel economy can only be obtained at high speed and high altitude; since the propulsive efficiency, which is a function of jet velocity/aircraft velocity, improves with speed. Therefore, in order to obtain better fuel economy it is necessary to fly fast and high.

It is clear, therefore, that the mating of a particular turbine to its proper airframe is a most important consideration and there is no doubt that the turbine propelled aircraft must be " tailor-made " to suit its engine, or vice versa. And, in order to determine the correct size and type of turbine for a particular aircraft, it is first necessary to know the following (aircraft) operating requirements: Speed, operational height, range and military, or pay load.

In the case of the turbine/propeller arrangement; this is more flexible in meeting the flight conditions of the various aircraft types of moderate speed—around 300 m.p.h. —and the propeller can be matched to the turbine and so designed that both will give the optimum efficiency in a particular aircraft.

It would appear that for high altitude and high speed—particularly in the case of fighter aircraft—the simple gas turbine/jet combination meets the case. But, for the lower altitudes and speeds and for large aircraft, the turbine/propeller combination will be used. I think there will be many applications of the latter, since it is not always feasible, or desirable, to fly at very high altitudes, or at extreme speeds.

The foregoing gives some idea of the future of the gas turbine. But there are a number of points, one or two of which I will mention here, that must be looked into in order to make the turbine a successful aircraft engine.

Turbines consume an enormous amount of air. This is in the order of 1 lb. per second per 50 lbs. of thrust. It is important to see that the air intake is properly designed and adequate measures taken to avoid ingress of sand and foreign bodies, etc., and also to see that there is proper protection against icing. At the same time, it is very necessary to avoid entry losses, which seriously affect the efficiency of the engine.

Gas turbines being, virtually, " full throttle " engines are affected quite seriously by the intake temperature and care must be taken to see that engines for aircraft which will fly to many parts of the world are designed with sufficient " capacity " to cope with take-off conditions in hot climates, as well as temperate ones.

It may be of interest to those who have not worked on turbines to know that the gas turbine cannot yet use the same air/fuel ratios as the ordinary piston engine. The piston engine uses the chemically correct air/fuel ratio of about 15:1, whereas that used in the turbine is in the region of 60-70:1. The reason for this high air/fuel ratio is that the temperatures must be kept lower than

those in the piston engine. But improvements in the future, mainly in regard to materials, will allow higher temperatures and, therefore, lower air/fuel ratios to be employed; although these ratios will still be higher than those of the piston engine.

The fuel consumption of the simple (Whittle) turbine/jet engine is higher than 1 lb. per lb. thrust per hour under " static " conditions; but we are now very close to this figure and it may be possible to get somewhat below it in the near future.

The various " staging " arrangements with blowers of the axial and centrifugal variety will, with propellers or ducted fans, or as simple jets, give still lower fuel consumptions. And we can foresee consumptions which are better than the "full throttle" or " take-off " figures of the piston engine; and which, in a suitably designed aircraft, will give better " air miles per gallon " than the piston engine, provided that the machine is operated at the best conditions for its power plant.

In addition to the various methods mentioned here for improving the operating economy of the turbine, there is very close collaboration with the material suppliers, to give us improved materials—for blades, etc. —which will allow higher operating temperatures and so further improve the thermal efficiency. Much valuable work has been done in this direction already.

Combining the two-stroke piston engine with the gas turbine, using the former, partly or wholly, as a " gas generator " and so enabling gases to be burned at high temperature and pressure before expanding them and leading them to the turbine, will give even better results than either the piston engine or the turbine, insofar as fuel consumption is concerned; and particularly where relatively low altitude and extreme range operation are required.

As regards fuels; the gas turbine generally uses " kerosene " or " vaporising oil," but " any old fuel " will not necessarily do because it may soot or " coke " the combustion system and impair the over-all efficiency. As a matter of fact, it is very necessary to have high combustion efficiency in gas turbines and, because of their large air consumption and relatively low thermal efficiency, the pressure drop through the combustion system must be kept as low as possible. And there must be no " flaming " past the turbine blades otherwise they will overheat.

It is quite possible that " additives " to the fuel will be evolved in the future, further to improve combustion efficiency; similar to tetra-ethyl lead in petrols and ethyl nitrate and cetane in the fuels used for compression ignition engines.

It must not be supposed that gas turbine fuel will necessarily be cheap and that there will be any particular advantage over and above petrol. Because, although the price may be about one half to two-thirds that of 100-130 grade fuel (at source), an equal amount must be added to each fuel to cover shipping and distribution charges. Therefore, if an aviation fuel costs, say, sixpence per gallon, at source, and a kerosene or vaporising oil threepence or fourpence; and tenpence or a shilling per gallon is added to each to cover distribution costs, the difference between the two is not so great as might be supposed. However, it is undoubtedly true to say that the fuel for the gas turbine will be somewhat cheaper than that for the high duty piston engine.

In view of the relatively high fuel consumption of the turbine, there is a strong case for the fuel companies to investigate the possibility of producing a fuel which will have a very high calorific value per unit volume. I mention, specifically, " calorific value per unit volume " because we can more easily deal with weight than bulk in the modern high speed aircraft.

It will be appreciated that the fuel for the gas turbine is, virtually, a " safety " fuel and, therefore, promises considerable advantages over the normal fuels at present used in piston engines. But, in my view, the

safety aspect will be mainly confined to the tankage and piping—the fuel installation—in the aircraft and not necessarily to the engine; because the engine is like a very large " blow-lamp " and, in the event of a crash, will ignite kerosene equally as well as petrol is ignited by the piston engine. The one possible advantage the turbine has over the piston engine is that there is not so much lubricating oil used because turbines generally run on ball bearings and, therefore, there is less hazard of ignition being initiated by lubricating oil.

As a matter of interest, I give in Table I the specific gravity and calorific values of various petroleum fuels. And it will be seen that, if a gas turbine could run on " heavy Diesel oil " or " boiler fuel," there would be an improvement in volumetric fuel consumption of the order of 15 per cent., compared with the present fuel used—" pool burning oil." But, unfortunately, apart from the undesirable features connected with the combustion of the heavier fuels—deposits, etc., it appears that P.B.O. is the heaviest fuel we can expect to get with a freezing point in the region of $-50°C$.

In Conclusion—Thinking Aloud

I have chosen this somewhat peculiar heading as an excuse to inflict upon you, at random, some of my personal thoughts on the future problems that face us in the air.

There will be big changes in the aircraft world in the next five or ten years and not the least will concern the power unit—the transition from the piston engine to the gas turbine; if not for every aircraft application at least for a large proportion of aircraft projected in this period.

The gas turbine, in " all-out " aircraft such as the intercepter fighter, will, in a very short period, bring us right up against " compressibility." And then it is very doubtful if we will gain anything by an increase in engine power, until the aircraft man knows how to go through the " compressibility wall." This may be a long-drawn out process, necessitating not only high speed wind-tunnel research, but, also, the more speedy solution of building and flying an aircraft particularly designed for this one purpose.

On this question of applied research, I cannot do better than recommend you to read Ricardo's Presidential Address before The Institution of Mechanical Engineers.

I doubt if we will ever see engines " buried " in the wing, except in the very largest aircraft of 200,000-250,000 lbs. all-up weight or thereabouts, or where a multiplicity

TABLE 1

Fuel.	Specific Gravity.	Calorific Value (net).		Ratio to P.B.O.		Ratio to 100/130 Grade	
		B.T.U.'s/lb.	B T.U.'s/I.G.	Per lb.	Per I.G.	Per lb.	Per I.G.
100/130 Grade ...	.720	18940	136580	1.021	9081	1	1
Cumene	862	17820	153600	.960	1.02	.940	1.124
Safety Fuel Alk. Bottoms... ...	.750	18820	141160	1.014	.9386	.9936	1.034
RDE/SF/1 ISO Dodecane ...	.771	18740	144460	1.009	.9605	.9891	1.058
Pool Burning Oil	.810	18560	150390	1	1	.9802	1.101
" " "	.801–.806	18590	148950–149880	—	—	—	—
Gas Oil	.850	18260	155230	.9836	1.032	.9641	1.136
Light Diesel Oil...	.870	18050	157040	.9722	1.044	.9529	1.15
Heavy Diesel Oil	.910	17980	163630	.9684	1.088	.9492	1.198
Boiler Fuel	.973	17800	173160	.9585	1.1514	.9395	1.268

of small power units are used. Thinner wings will be made, engine powers are increasing and it is just not possible, in my opinion, to hide the engine completely. Possibly, engines may go in the fuselage, in certain aircraft types; with suitable vibration damping and installed in fireproof compartments, insulated for sound and heat.

The advent of the gas turbine, because of its much lower weight, may bring about an increase in the structure weight of wings; since it (the turbine) will contribute less to the relieving loads and more " meat " will have to go into the wing itself.

This, of course, applies equally and even more so to engines installed in the fuselage. But, in the latter case, the result of having a wing completely free from lumps will more than compensate for its greater structure weight.

Future propellers must be developed to be completely independent of the engine oil system—the whole operating mechanism being incorporated in the propeller hub. It must also be proof against freezing. And it should be designed so that the blades will go into a safe *coarse* pitch in the event of a failure of any part of the controlling mechanism. The governing of the propeller, operating under constant speed conditions, should be " dead-beat." The maximum rate of pitch change available must be sufficiently high to cover the feathering, braking and baulked landing cases—about 45°-50° per second.

It is considered that propellers can be used without serious drop in their efficiency at (maximum) aircraft speeds of 500 m.p.h. and possibly between 500 and 550 m.p.h. But it will mean the use of very thin blade and root sections and the blades must be rigid and not suffer from " flutter " at these speeds. In this connection I think the hollow steel blade will have to be considered.

We in this country have always fought shy of this type of blade because of the big design, production and repair difficulties involved. It has been recognised, however, that there is a saving in weight with the hollow steel blade, for propeller diameters above (approx.) 13 ft. But I am now practically convinced that the hollow steel blade will come in for the smaller diameters, particularly for these extremely high speeds —although the propeller itself will probably die, just so soon as we can employ the turbine/jet economically in those machines suited for such speeds.

In addition to its smoothness of operation, the gas turbine of the simple " jet " type will be silent, so far as the passengers and crew are concerned. But when fitted with a propeller there will be some noise, which may be more tiring and irritating than the combined noise effect of the propeller and exhaust of the conventional engine. This problem will be similar to that of the modern automobile, where the engine was developed to a high degree of silence and then people complained of the various noises and squeaks from the chassis and body. When these were largely eliminated the next source of irritation was the noise of the wind past the body and particularly when the " Fisher " type ventilating windows or louvres were fitted! I am sure, however, that modern sound-proofing technique can go a long way towards eliminating those noises which tend to make journeys by air so tiring.

When peace descends upon us, the Royal Air Force will be left with obsolete aircraft and only makeshift aircraft for transport purposes will be available.

From the military angle this will also be true of other Nations; since although war speeds development, its needs and wastage are so gigantic that it is often difficult, if not impossible, to stop or even reduce production on current engines and aircraft in order to introduce new types, if these cannot be got into production quickly and in sufficiently large numbers for the war. Therefore, an entirely new development may not progress quickly in war-time; unless it is of vital urgency.

This country, due to its small size relative

to America and because we have been at war for a longer period than America, has its whole industrial effort concentrated upon munitions, with little or nothing to spare for any new development not directly applicable to war.

America has an advantage over us because of her great natural and industrial resources. And she has had further advantage in entering the war after ourselves; allowing her to profit from our experience and mistakes.

Since we had not the extra capacity, it was agreed that America should build transport aircraft for both Nations. Even although these were mainly for military use, some were direct adaptations of civil transport types and more modern types are in build and projected.

America will inevitably have a considerable lead over ourselves in the construction of transport aircraft. But, after all, we will be in the same position in regard to transport aircraft as America has been in military aircraft; just as she must have profited from our experience in the latter case, we should profit from her experience in the former and go out to develop and build even better transport aircraft than she.

On the military side we have first to visualise what type of aircraft will be needed ten or twenty years hence and we can only do this by considering the probable political position at that period.

Since we are never likely to be an aggressor nation and more likely to be the target of an aggressor, we should consider the rebuilding of an up-to-date air force, in two phases: (a) The first covering, principally, defensive types, with some strategic types; and (b) the second, to be brought into operation quickly after the start of war, to provide suitable offensive aircraft for the propagation of the war.

For phase (a) and assuming a European war, we could then develop, in the next five or ten years, extremely high performance interceptor fighters for the defence of this country. And very high speed medium-sized bombers of sufficient range and load carrying capacity to harrass the aggressor, whoever and wherever he may be on the European continent. Cadré, or skeleton, squadrons of these machines could be formed and, with a nucleus of picked pilots, experience would be gained of the tactics to be employed. The main strength of the Royal Air Force would then be gradually transferred to these new types as they become more fully developed.

From our experience of this war, however, it does seem to me that, from the European standpoint, the aircraft as we know it to-day, with a pilot or pilot and crew, will only be used in a relatively limited way; because I can foresee developments in the use of the large rocket and also, " Radar "-controlled missiles, which may be expendable—such as the flying bomb—or pilotless aircraft capable of being accurately directed to drop their bombs on the target and then returned to base. I can visualise also pilotless aircraft, similarly controlled, for photographic reconnaissance.

The result will be that the aggressor nation will, without warning, project all these unpleasant things upon us and the only (relatively) conventional aircraft he need use are troop transports, which will come across after the attack for the purpose of occupation.

Therefore, the only use we could make of our interceptors and high speed bombers, under such conditions, would be to shoot down any " Radar "-controlled and pilotless aircraft coming over this country; and to bomb heavily, at a high rate, the rocket and aircraft launching sites of the aggressor.

This assumes, of course, that we, by our Intelligence system and various " Radar " developments, can have some idea of the aggressor's intentions and movements before it is too late.

My grateful thanks go to my colleagues in M.A.P. for " vetting " certain sections of this paper. Since it is my own work they

are not in any way responsible for the views expressed, which are entirely my own and do not necessarily represent the official views of the Ministry.

DISCUSSION

Dr. H. R. Ricardo (President, Institution of Mechanical Engineers, Fellow): He felt somewhat at a disadvantage in discussing Air-Commodore Banks' excellent paper, because he could find in it so little with which to disagree or to argue about.

In view of the rapid development of the gas turbine, he felt it was a waste of time and energy to attempt to develop piston engines of the conventional form of over, say, 3,000 h.p.; but that was not to say that he was yet prepared to utter a funeral oration over piston engines in general. The advent of the turbine should and would, he hoped, make the piston engine pull up its socks; and there was still plenty of slack to be taken up, especially in the way of fuel economy.

During the war their first and foremost demand had been for power at all costs and, as the author had pointed out, amazing results had been achieved in that direction, but only at the price of fuel economy and by the aid of very strong stimulants in the way of special fuels.

The fuel consumption of a piston engine was a function of the expansion ratio that could be employed, the power a function of the amount of oxygen that they could stuff into it in a given time. In order to stuff as much oxygen as they could into the cylinder, they carried out the compression in several stages, but the expansion in one only, and even that had had to be curtailed. By so doing they outraged the thermodynamic laws and had to pay the price in heavy fuel consumption and the need both for intercooling and for ever higher octane fuels.

Dr. Ricardo agreed entirely with the author that there was little case for developing special engines for civil transport. He pleaded rather that, for civil use, they modified the existing highly-developed military engine merely to the extent of increasing its expansion and lowering its first stage compression ratio. That done, it should be possible, straightaway, to get down to a consumption of 0.40 lbs. per shaft horsepower hour, and that on ordinary 100 octane fuel.

By so doing they would lose considerably in take-off power; but to-day they knew of several ways of accentuating temporarily the power of an engine, so that they need not worry overmuch on that account.

Expressing agreement with all that the author had said about the very great advantages of the turbine, Dr. Ricardo joined with him in paying tribute to Air-Commodore Whittle for his masterly pioneering work in that field.

The snag about the turbine, of course, was its heavy fuel consumption, and that was rather a fundamental snag. On the other hand, its mechanical efficiency was virtually 100 per cent., which stood it in very good stead, more especially at high altitudes, where the mechanical losses of the piston engine were apt to bulk very large. As in the case of the steam turbine, they could do something to improve its efficiency by heat regeneration, inter-stage re-heating, etc., but those fluences added considerably to its bulk and weight. They could not, as in the steam turbine, extend the expansion ratio by condensing.

The efficiency of any heat engine depended on the range of temperature through which it could operate. The combustion, in reasonable time, of any hydrocarbon fuel in air gave rise to a temperature ranging from 2,500° to 3,000°C. absolute, depending on mixture strength, compression ratio, etc. That temperature was the starting point in either the piston engine or the turbine. Unfortunately, the turbine could not digest a temperature much in excess of 1,000°C. absolute. In order to bring the temperature down to that level they had to supply a very

large amount of dilution air, some four times that of the combustion air. If that dilution air were a free issue, it would not matter; but unfortunately it had all to be handled and compressed by a blower, whose efficiency was substantially less than 100 per cent.

The piston engine, on the other hand, could cope with temperatures of the order of 2,500°C. or more, and so could drink its working fluid neat, but, unfortunately, could not usefully expand it down to below about 1,500°-1,600°C. Thus, the piston engine and the turbine resembled Jack Sprat and his wife!

Surely the obvious line of development was to marry the two, using the piston engine to deal with the small volume, but high temperature part of the heat cycle, and the turbine with the large volume low temperature. Between the minimum temperature of discharge from the piston engine and the maximum that the turbine could at present accept there was still a certain gap; to bridge that gap some, but relatively only a little, dilution air would be required. That was a pity in some ways, but they could make a virtue of necessity, for the presence of excess air at once rendered attractive the use both of the two-stroke cycle and of compression ignition. Of the two-stroke cycle because it could deal, with advantage, with a greater volume of air than its cylinder volume defined, hence a much smaller cylinder capacity would suffice; of compression ignition because the presence, in any case, of excess air in the cylinder removed the main handicap to Diesel operation, namely, that it was not possible to consume the whole of the air in the combustion chamber.

Apart from the use of heavy oil, the compression ignition engine, in such an application, would have other important advantages, more especially in the way of control.

On some such lines it should be possible to realise an overall efficiency far in advance of anything which had yet been achieved, or was in sight with either the piston engine or the turbine alone.

In the paper the author had referred to such an arrangement; indeed, many such had been proposed during the last fifteen years, but hitherto they had lacked sufficiently developed ironmongery to deal with the low pressure end.

The experience now available with turbines and blowers of large power has brought the application of such a combined unit into the realm of practical politics, more especially for long range aircraft.

Air-Commodore WHITTLE (Fellow): The author had dealt very fairly with the prospects of the gas turbine and there were no points on which he was in violent disagreement; but that did not mean that he agreed with everything. The subject was a very big one and the author had achieved quite a feat of compression; but one would like to amplify some of the points made and modify the emphasis on others.

The effect of the reduction of temperature with height in improving the efficiency of the gas turbine was not due only to the increase of compression ratio for a given speed. A very important factor was the increase of the positive-negative work ratio of the constant pressure cycle for a given maximum combustion temperature. The positive-negative work ratio was very important with the order of efficiencies which were at present obtainable in compressors and turbines. The author had really covered the point in his reference to the improvement of the temperature ratio across the engine; but perhaps that would seem a little obscure to many. The positive-negative work ratio was so important that it imposed a limit on the raising of the compression ratio. One could not just obtain more efficiency by raising the compression ratio indefinitely; there was an optimum value of the compression ratio for a given maximum temperature and component efficiencies.

The effect of aircraft drag was even more important with the gas turbine than with the ordinary aircraft engine of the piston type, and especially with the jet propulsion gas turbine, because the thrust horse-power developed with the latter was almost linear with the speed; hence, anything that was done to reduce drag automatically increased engine power. With the petrol engine and airscrew there was a tendency in the opposite direction at very high speeds owing to the fall off of propeller efficiency.

However, the effect of reduction of drag on the power required for climb and take-off was not very great. Hence, as aircraft drag was reduced, the gap between maximum power and cruising power continually increased. The power-height characteristics of the gas turbine were such that power plant having adequate maximum power for take-off and climb provided economical cruising power at heights of the order of 36,000 feet.

The author had hinted at the many possible variations in the form of the gas turbine; that was one of the factors which troubled gas turbine designers. To the large number of permutations and combinations possible in the arrangement and type of the main organs must be added the possible variations in the linear scale. In fact, the linear scale of a given arrangement was infinitely variable within wide limits. These possibilities of variation presented the gas turbine designer with a very difficult problem. In order to fix his design, he *must* know the job of work the engine was going to do. The author had pointed out that aircraft and engines must be tailor-made to suit each other; and the same point was made by Sir Roy Fedden in his Wilbur Wright Lecture. It could not be made too often or with too much emphasis. With one or two exceptions, up to the present the gas turbine designer had been designing in a vacuum. In short, as compared with the reciprocating engine, the gas turbine provided many more possibilities of variation, but each arrangement was much more specialised.

In Air-Commodore Whittle's opinion the author had over-emphasised the high fuel consumption of the gas turbine; and Dr. Ricardo had also had a crack at it. But that was not an intrinsic characteristic of the gas turbine, if one bore in mind the job of work for which the power plant was intended. Much lower fuel consumptions per T.H.P.-hour than those obtained at present were possible at the price of increased complexity and weight, and whether or not it would pay to go for it depended again on the work the aeroplane had to do. For some purposes a simple gas turbine of relatively high fuel consumption measured in terms of thrust horse-power could show such a saving in power plant weight that the fuel consumption in proportion to pay load carried was actually lower than for normal power plant. In illustration of that he mentioned that a well-known aircraft designer, having a very high performance specification to meet, had made rough designs of two alternative aeroplanes, one with gas turbine jet propulsion and the other with the normal piston type power plant; the one with the piston engines worked out at more than twice the all up weight of the other and had to carry more fuel for the same duration of flight and for the same military load.

Air-Commodore Whittle predicted that, even though the gas turbine might never show a fuel consumption as low as the piston engine in terms of thrust horse-power, nevertheless it would be possible to get a greater value of the product of range and percentage of pay load with the fast gas-turbine-engined aeroplane than with the relatively slower piston-engined aeroplane.

The criterion of the fuel consumption in terms of static thrust was very unsatisfactory for general purposes. It was useful for comparing the effect of changes on the behaviour of a given engine on the bench, but that was almost the limit of its useful-

ness. An engine which appeared to be better than another on that basis might in fact be substantially worse under all flight conditions; but it was difficult to say what to suggest as an alternative, especially for jet engines.

Finally, he thanked the author for having described him as the "Charles Parsons" of the aviation power unit, for one could scarcely have paid him a higher compliment. He thanked Dr. Ricardo also for his kind remarks.

Mr. N. E. Rowe (Director of Technical Development, M.A.P., Fellow): The lecturer has used the occasion for a general browse over the field of engine design and development which has been instructive and useful. He has contrived to give a very stimulating lecture in which he has been both prophetic and challenging. He would like to examine the implications of the lecturer's title a little more closely. No one can deny that engine development is of vital importance; it is that process of moulding, improving, refining, which is of the essence of progress in dealing with such a highly complex mechanical device. They had seen the process at work here in war-time in a way unexampled probably in any country in the world. But what are the directions in which engine development has its greatest importance for all of them in the aircraft field?

There are many aspects, of which the British aircraft industry has made itself complete master of at least one, namely, the art of squeezing the last vestige of power out of each cubic inch of cylinder volume. The whole trend of development over many years has been in this direction, and it has, indeed, served them well in the present war. Doubtless this policy was dictated by military considerations. They could, however, have concentrated on other aspects of development, for instance, complete reliability, safety, maintenance, improvement in detail design to cut down the weight, and, last but possibly most important, improvements in economy. They have surely now reached the stage when these other aspects must receive more attention, and he was glad to hear the lecturer refer to 1,000 hours between overhauls and specific consumptions as low as .38 lb. per b.h.p./hour as near objectives. They could not have such developments brought to fruition too soon. Fuel economy influences aircraft design in a fundamental way for all types, but particularly the long range aircraft, where it is quite the most important parameter in determining overall weight for a given task or specified requirement—the better the fuel economy, the smaller the aircraft for a given duty.

In his view, all their classes tend to be getting too big and heavy for their duty; improved engine economy is one of the very best ways of getting the smallest aircraft for a set task. This insistence on economy does not exonerate the aircraft designer from his part of providing economy in structure and cleanness of the aircraft form. Indeed, the latter is of the greatest importance with turbine jet arrangements because drag, thrust and economy are all implicitly related. Clearly from now on they must have the closest integration in design of the power unit and the airframe. There cannot be too close a liaison between the engine and aircraft designers throughout the course of a new design, but especially at the earliest stages of the conception of a new project. This is a rather novel idea for most of them, but he was convinced it is of equal importance to that of the development of the power unit itself. The power unit from now on will enter so intimately into the overall aerodynamic and structural conceptions of the design as a whole, that they are likely to fall far short of the possible optimum if they do not have this very close link-up.

There are a number of points in the paper on which he would like to comment, particularly the part materials development has played, and must continue to play, in the

development of the power unit. This is equally true in the whole field of aircraft development, but here the emphasis is on fundamental research. They wanted to know more about the way in which materials obtain their qualities, their structure and how to control it, particularly how to control such fundamentals as the moduli of elasticity and rigidity.

Maybe a search for better materials will help them in their radiator and oil cooler problems. He was in entire agreement with the lecturer that there was a very great field for improvement here, and also for a new attack on the radiator problem, or rather the problem of cooling the coolant. He would like to see new minds and methods brought to bear on this, and the more novel the form of attack the better. It is a very real embarrassment to aircraft designers to be called on to accommodate more and more in less and less space, and the radiators and oil coolers now required to make aircraft fit for use in all parts of the world, are one of the most serious problems in new projects. From this point of view, the direct cooling of the air-cooled engine is most attractive. The lecturer rather lightly skated over distribution as affecting economy, but it most certainly is of great importance in relation to cooling, and hence economy, because of the drag involved in the cooling process.

They were undoubtedly at the commencement of another period of rapidly mounting cruising speeds in all classes and, hence, every effort is needed to keep wings free of excrescences, especially at the higher values of Mach number. They may, therefore, see many more layouts with engines in the body, and this form may lend itself particularly to jet propulsion. He did not think with the lecturer that this will necessarily lead to heavier wings, since much of the structure weight is likely to be decided by consideration of stiffness rather than strength at the speeds in mind. Moreover, such is the demand on physical space that wings of long range aircraft may be filled with fuel to the tips, which would of itself give a relief on structure weight. He did not agree either with the idea of a compressibility wall. He thought a more apt analogy may be that of a craggy hill rapidly steepening from the current plain and more and more rough and boulder strewn as the climb progresses, with the top in sight but a very difficult path to it.

The ultimate size of engines is a controversial topic. In his view, for military aircraft of, say, 25 tons and upwards of the medium and long range class, the size should be such that they could have no more and no less than four propeller discs or axes of propulsion. But such general standards may well be swept aside sooner rather than later with the rate of development now foreseen. In civil passenger transports for instance, it may be advisable to have layouts with three or four engines at much lower aircraft weights to ensure the very best standard of safety. Much will depend on continuance of the propeller for converting rotational energy into axial thrust. He thought there was still a great future for it since it would give flexibility over a wide height and speed range with either reciprocating or turbine power units. The Mach number of cruising flight will probably be the determining parameter and he would expect the propeller to persist even up to speeds of say 540 m.p.h. at 35,000 ft. in suitable classes. Intensive research and development is needed on plan forms, profiles, tip flow and particularly vibration. The latter is a subject on which he would like to see very much more attention concentrated in this country. It is a field for combined operations of the power unit, propeller and aircraft designers and engineers, a complex field which requires hard and patient effort but is likely to repay it all. They must endeavour to reach the position when they are able to design free from vibrations, particularly in civil transports. The problem tends to become more acute with a trend towards lower power loadings

and higher wing loadings and hence "denser" aircraft. May they not look for a technique of model investigations similar to that which was so successfully used in the classic work on aircraft flutter? He would like to hear the comment of aircraft designers on this point.

Before closing, he could not refrain from referring again to fuel economy. To obtain the optimum designs of aircraft they wanted this and they wanted it speedily. The combination of two-stroke piston engine with gas turbine in the form suggested by the lecturer sounds particularly attractive. No doubt this is a longer term development, but they all hoped it will be given the most serious attention.

In the meantime, with turbine engined aircraft they would be faced with the demand for much more fuel for a given duty because in a given weight of aircraft the lower weight of the power units is balanced by the weight of the additional fuel needed. A most serious problem may grow out of this, especially from the military point of view. He would like to see the greatest possible development of suitable fuel supplies within this country; could the lecturer give any indication of the prospect of this, using perhaps our coal resources in a more enlightened way?

Group-Captain P. W. S. BULMAN (Fellow) : He complimented the lecturer on the manner in which the paper had been presented; it was reminiscent of the way in which most of the important work of the world was done, the technical discussions over the lunch table or extending far into the night, when, with something at one's elbow, planning had seemed so easy and pleasant. Such was the atmosphere Air-Commodore Banks had created and brought to the meeting and in so doing he had avoided the necessity of evaluating the hard facts and figures of the volume of engineering which had to be tackled by designers and engineers before these wonderful day dreams took practical shape. This thought would, however, give encouragement to those who were laying the foundations for training the many young scientists and engineers who would be so essential in implementing these plans for the future.

The volume of work involved could best be estimated by an examination of the word " development," which the lecturer had used some five or six times in the early part of the paper, each time in a different sense or perhaps different tense. It ranged from the pre-design development of essential components, through the stage of type test and flight test and " debugging " right through to later development of the engine to higher powers and efficiency. All these stages were necessary, but they should not forget that one ounce of development in the early stages was worth thousands of pounds in the post design or production stages.

The author had used the word " unit " in the title of his paper and one wondered what he had meant thereby. Whilst in the main it appeared that he had used it in the correct sense, as meaning the complete power plant, one noticed that he had lapsed into the old bad habit of considering just the engine itself. He had even considered the radiator and oil cooler as separate parts, although admittedly he had included the induction and exhaust systems. There was nothing so dangerous as to consider the engine alone in the early stages, if in so doing one leaves some essential installation or operational problem to be solved at a later date by other people.

In a friendly criticism of the author's opinions concerning the jet engine, Group-Captain Bulman commented that he had evidently joined the fashionable throng of jet super-optimists. Group-Captain Bulman did not wish in any way to decry the jet engine; he thought it might well prove as epoch making as the early rotary engine, but it was perhaps, at present, as undeveloped. Indeed the author had only claimed low weight,

smoothness of operation and smaller requirement of lubricating oil as advantages of the jet engine and had gone to some length to indicate the extent of the complications that development would bring in its train.

Dr. H. Roxbee Cox (Fellow) : He was another super-optimist in respect of the gas turbine. Most of the points he would have liked to have made with regard to it had already been made far better by Dr. Ricardo and Air-Commodore Whittle.

However, it was his intention to refer briefly to the purpose of the paper as expressed in its title, and also to voice his regret that the author had not seen fit to recite at the meeting, as one had hoped he would have done, the excerpt from his favourite tragedy which was quoted at the beginning of the paper!

There were in their craft, he continued, two great mysteries—research and development. The definition of those terms was difficult. On the extreme left of the research end of the spectrum of technical progress there was the quest for basic truth. At the extreme right of the development end of the spectrum there was the manifestation of truth in the form of hardware. But as they approached the middle of the spectrum, definition became more and more vague, and no one really knew where research ended and development began. They were in fact indivisible, and although in an organisation it might be found convenient to have a research department and a development department, one might well find the research department accused of doing development and the development department accused of doing research.

Because research had been responsible for attractive ideas like splitting the atom and bending rays of light, it had achieved a considerable dramatic appeal. Development *qua* development did not provide such exciting ideas; it was a far more humdrum affair. Consequently when, as happened so frequently, it was discovered that some British industry was years behind the times, there was a cry for more research. But very rarely did one hear a plea for more development; he wished it were heard more often.

In point of fact, research and development were equally important and were part of one process; and such a paper as that by Air-Commodore Banks, which placed development in its true perspective as a major engineering function, did a service which could be acknowledged with gratitude. However many brilliant theories might be developed and however many important facts might be established by research, they would be of little use without intensive and systematised development to translate them into the actual service of mankind.

Air-Commodore Whittle had already discussed the author's views on the fuel consumption of the gas turbine. All that one could add was that the current habit of considering fuel consumptions in terms of lbs./thrust h.p./hr. or lbs./brake h.p./hr., as the case might be, was apt to be misleading. The gas turbine was a power plant for high-speed aircraft, and it must be remembered that if aircraft "A" travelled twice as fast as aircraft "B," but the power plant of aircraft "A" consumed fuel twice as quickly as the power plant of aircraft "B," then "A" and "B" would consume the same amount of fuel in a given distance. So that it would be very rash indeed to assume that, because a power plant had a higher fuel consumption on the usual hourly basis than another, it was necessarily less economical when in operation in the air. He believed, with Air-Commodore Whittle, that the greatest overall economy would be achieved with the gas turbine even if it did not achieve fuel consumptions on the lbs./hr. basis as low as those of the piston engine; though he believed it would do that as well.

It was interesting to learn that the author believed it would never be possible to bury engines completely in wings, although he had

made exceptions in the case of very large aircraft or those having a great multiplicity of power units. He might be right. But it had not yet been proved whether the lowest drag was obtained with a large fuselage and highly-loaded thin wings with large protuberances, or a minimum of fuselage with a lightly-loaded wing capable of embracing the engines and most of the rest of the load. Moreover, it might be possible to install a relatively large number of very small gas turbine engines across the span, and Dr. Roxbee Cox felt that it would be worth while for designers to explore the possibilities of such a scheme before dismissing it. There was always a tendency to believe that progress was associated with more and more powerful units; but that was not necessarily the case. The real criteria depended on the job to be done, and included factors such as thrust per unit weight, thrust per unit frontal area, and fuel consumption (though not necessarily on the hourly basis).

It was also very interesting to find that everyone subscribed faithfully to the doctrine that the gas turbine engine and the airframe must be designed together and each made to suit the best overall design of aircraft. The time had come for someone to do it. Air-Commodore Whittle had suggested that it had in fact been done in one or two cases; but Dr. Roxbee Cox did not believe it ever had been done. Aircraft designers must really believe that the gas turbine was Protean in form and provided the opportunity for ideal aerodynamic and structural layouts which the rigid geometry of the reciprocating engine frequently prohibited.

So far he did not feel that the aircraft designer was being very enterprising in his applications of the gas turbine. Too many of the layouts were just ordinary aeroplanes with invisible propellers. That *might* be the right formula, but they should try some much less conventional ones before deciding that that *was* the way to exploit the gas turbine to the full. They would probably have some failures, but they might find a winner. The time had come, as the Walrus and Air-Commodore Banks had said, to talk of many things. In fact, the time had come to *do* many things, to throw their technical bonnets over the windmill—or over the ducted fan. Their development organisations must be strengthened so that they could produce new prototypes in great variety at great speed. Let them go to it. " To-morrow to fresh woods and pastures new." The operative word was " To-morrow."

Mr. TRESILLIAN (Associate Fellow): He would like to consider the comparison between sleeve and poppet valves. At present they gave approximately equal valving in existing engines. As pointed out many years ago by Dr. Ricardo, the maximum port area obtainable in sleeve valves was fixed by the motion of the valve and could not be increased.

However, there were still possibilities of development in poppet valves, and there need not be any limitation on piston speed.

Increased valve area could be provided by abandoning the seat insert and using steel heads or steel-lined heads, and further by a change to the three-valve penthouse arrangement which favoured inlet valves, usually the limitation. At least 25 per cent. more valve area could be obtained, and valving experiments showed that, other limitations apart, piston speed could be increased roughly in proportion to the inlet valve area as a percentage of the piston area. If valve gear speed could also be raised, piston speeds could be raised by increasing engine r.p.m., without increase of stroke. From investigations of existing four-valve engine valve gears it appeared quite possible to increase the operating speed from 3,000 to over 4,000 r.p.m., even retaining the existing valve springs, purely by changes in cam and rocker kinematics, which were not by any means the best on modern engines.

With regard to the 28-cylinder engine

having four cylinders along and seven around, he said that that arrangement involved in each vee an inlet pipe, exhaust pipe, inlet cooling air duct and outlet duct and ignition cables, since there was an odd number of vees.

The 24-cylinder arrangement of four along and six around could be made much simpler, since it had an even number of vees. It could have three containing only the inlet pipes and air outlet ducts, and three containing only the exhaust pipes and air inlet ducts. The cooling duct area would be much increased. A split crankcase could also be used, which might therefore be made of castings.

Any engine having a four-throw crank had a great advantage if it could use the alternately opposed or zigzag crank arrangement, which gave very low bearing and crankcase loads. Experience had shown that all aero engines having three-throw or six-throw cranks had involved a lot of bearing and crankcase development owing to the high average bearing loads. Crankcase development could be very slow.

The author was quite right to suggest that 24 cylinders should be enough for any engine. An investigation of power/weight ratio against numbers of cylinders on existing engines showed that there was no further gain in power/weight ratio after about 18 cylinders.

Finally, in stressing the enormous importance of better installation engineering, Mr. Tresillian said that airframe failure by direct breakage in the air was rare. Engine failure directly was not common. Failures of installation equipment were much more frequent, and of engines due to faulty engineering of oil systems, fuel, cooling, air intake systems or engine controls. With all that we had already done, the design technique of installations was still far behind that of airframes and engines.

Further, any Air Force that was in the growing stage and was trying to accumulate aircraft might find its mission rate controlled by its loss rate. Simple arithmetic showed that if an Air Force used half its aircraft on each mission, went out five times per month and lost four per cent. on each mission, then the entire combat Air Force and crews must be replaced in 10 months. If the losses could be cut to two per cent., the same number of aircraft could go out 10 times per month instead of five times for the same replacement rate. Newspaper reports had shown loss figures occasionally higher than four per cent. Therefore, the Air Force with the least vulnerable installations and power plants could operate more frequently.

Repair time might be another limitation on flying effort, and was much affected by the complexity and poor access of power plants. Many of the pipes and complications in power plants could and should be eliminated by re-arrangement of engine components and accessories. For example, there was no real need for more than one fuel pipe and one oil pipe in a power plant; the accessories could be re-grouped to eliminate the other pipes. Engine designers should realise that that kind of engineering was a most important part of the war effort.

The performance of an engine on its test bed was largely defined by the power curves and endurance test. When installed in a bomber those were only two of many aspects. Others equally important were the mission frequency and mission life of the aircraft.

Mr. B. A. Duncan (Associate Fellow): They had grown accustomed to comparing the reciprocating engine of to-day with the gas turbine of to-morrow, and tended to discount any further development of the former.

Confining his own remarks to reciprocating engines, he suggested that the author's comments on the relative merits of sleeve valve and poppet valve engines were a little unfair, since he was comparing two things which were not quite comparable. Poppet valves had been developed over 70 years, whereas

sleeve valves had been developed over about 18 years. The sleeve valve engine had reached a stage at which it was an entirely practicable production proposition; it had just reached or was just reaching the crest of the first wave, and there were others which it had to get over. With big cylinders and a good induction system, the sleeve valve engine could be run at piston speeds 20 per cent. in excess of the 3,250 ft. per minute quoted by the author. It was also true that poppet valve engines could be run at very high speeds; but he believed the sleeve valve engine could accommodate the very high piston speeds more easily and simply.

The maintenance comparisons made by the author as between the poppet valve and sleeve valve engine were presumably based on statistics, and therefore one could not argue about them. Recently he had read in the S.A.E. Journal (for January, 1945) an interesting article by Cyril A. Rowe dealing with freight and passenger aircraft operation in America, and containing an analysis of some 800 power plant failures, 300 of which were concerned directly with poppet valve gear (cam assemblies, and valves broken, burned and stuck, etc.). That was a very high percentage indeed, and those failures would not have occurred if sleeve valve engines had been used. The parts of the sleeve valve engine were simple and robust, and once the engine had been put through its development, such troubles would not occur.

Coming to the problem of air *versus* liquid-cooling, Mr. Duncan urged that, given the same installed weight, the air-cooled engine could have just as good heat capacity factor as the liquid-cooled, using well-proportioned fins and high-conductivity material where necessary. Both must have a fan or exhaust ejector cooling in any case. He did not believe there was anything to choose between them. He agreed that the air-cooled in-line engine was clumsy in units of very high powers, but for powers up to, say, 1,000 h.p. the air-cooled in-line engine could be very satisfactory and compact.

As to the comparison between in-line and radial engines, it seemed that the author of the paper favoured the in-line, presumably because he considered the aim should be to have as few cylinders as possible per crank-pin. But nine cylinders per bank had been used for many years and had proved satisfactory. One engine of 11 cylinders per bank had been made, or contemplated. Surely there was plenty of scope for the two-row 18-cylinder radial air-cooled sleeve valve engine of up to 6½ in. bore, as opposed to the 6 in. bore which is more nearly the limit for the poppet valve engine. It would be difficult to beat in the " Carter Paterson " type of civil aircraft for the next seven or eight years. Crediting it with 12 times R.A.C. rating, it should give 3,650 h.p.

The main asset of the piston type engine was its low fuel consumption, and he believed there should be much more development of it towards this end before it gave in to the turbine. It was a pity that the Diesel had not been developed more; but Dr. Ricardo and others had discussed the combination of the two-stroke Diesel with the gas turbine.

Bearing in mind the four-row " Pancake " Diesel engine made by General Motors, Mr. Duncan suggested a layout for a large reciprocating engine for use in the long range " Carter Paterson " machines, flying boats and over-ocean military reconnaissance machines. He had in mind a six-row, liquid-cooled, 90°, sleeve valve, two-stroke, with single piece crank and slipper rods, in conjunction with a gas turbine, as proposed by Dr. Ricardo. Such an engine, of 6½ in. bore, should form the basis of a valuable high power unit.

Mr. F. Owner (Fellow): The discussion of the paper was rendered quite difficult by the very deep conviction with which he shared the author's views on aero engine development and the importance of its

timing. Being as fervent an admirer of Lewis Carroll as were Air-Commodore Banks and Dr. Roxbee Cox, however, he repeated his favourite quotation from " Alice through the Looking Glass," because it was so peculiarly relevant :—

> " We've been running a long time," ventured Alice, doubtfully, " and we don't seem to have got much further." " Of course not!" snapped the Red Queen, " let me tell you, in this country you have to run very fast to stay where you are. If you want to get anywhere, you must run ever so much faster than that!"

The importance of " timing," which Air-Commodore Banks italicised in the paper, could hardly be exaggerated, and particularly the timing of power unit and aircraft development needed more synchronising than it had received in the past. In the case of turbine units it was necessary that the research and development programmes should dovetail with the corresponding aircraft work in addition to " tailoring " the turbine itself to suit its aircraft. In particular, the use of turbines would open the way to many novel possibilities in controlling or modifying the airflow over the aircraft surfaces, and that investigation must necessarily be a joint affair.

In reviewing the importance of development work, he asked for the author's opinions on two questions of policy. The first was the application of the old Roman idea " divide and conquer." Was it not more important now than ever to develop each separate section of any proposed new power plant separately, with its own appropriate test plant, thus limiting and controlling the number of independent variables?

Secondly, inasmuch as development nearly always tended towards increased complication, he entered a plea for simplicity wherever it could be achieved. Very often, he said, the amount of complication of a design varied inversely with the amount of design thought put into it. The general trend of increased complication would no doubt apply to the gas turbine as to most things hitherto, but it was to be hoped that only those unavoidable complications which earned their keep would be added to what was an inherently simple type of power plant.

As an example, he said the complication of the exhaust turbo might have to be incurred in order to utilise energy otherwise wasted in the reciprocating engine's exhaust. If, however, that energy had to be returned direct to the crankshaft instead of the supercharger, the inherent inflexibility of such an arrangement might drive us perforce to the additional complication of multi- or infinitely-variable speed gearing.

Finally, he asked if the author would agree that we were only yet at the outset of fuel investigation for gas turbines. Fuel development for reciprocating engines had been very largely directed to the factor of detonation, which was not an issue at all in the turbine. Attention could, therefore, be directed to safety, low vapour pressure and high calorific value, which were primary qualities. The importance of a safe and cheap fuel to the future of aviation needed no underlining, and he would value the author's opinion on the rate of progress which the development work on gas turbine fuels might reasonably be expected to produce.

Mr. A. R. Ogston : He was impressed by the author's conviction that all the piston engines really were going to be superseded within the next decade. Incidentally, that innovation also meant that millions of pounds worth of oil refinery equipment for manufacturing high-octane aviation fuel would likewise become redundant, although it was true that that equipment could be diverted to the production of higher-grade petrols for motor cars, where, owing to its greater flexibility, the piston engine would remain supreme for many years. Nevertheless, as the author had indicated, they would still

witness appreciable further developments in the reciprocating aero engine, and Mr. Ogston suggested that the use of still higher grade fuels offered the piston engine the best prospect for competing with the gas turbine.

Perhaps the author had been rather pessimistic in doubting whether the super-high-octane fuels, to which he had referred, could be made available for a long time to come. Mr. Ogston believed that if they were required they could be made available just as soon as the European and Japanese conflicts had ended, in view of the very considerable shrinkage in the total demand for aviation fuel which would then occur.

He was interested to hear the author's opinion that there was unlikely to be any real gain in increasing compression ratios above 7 : 1. If that were so, it rather suggested that at least the 130/160 grade fuel might not be necessary. It would be useful to know his views on what was likely to be the grade of fuel necessary for the type of engine envisaged with 7 : 1 compression ratio.

Again, he was a little surprised by the low figure of 35-40 per cent. which the author seemed to imply was an optimum cruising power for engines developed to give high take-off power. His previous impression was that an optimum ratio of cruising to take-off power for the average transport aircraft was at least 50 per cent.; in fact, he had seen recent analyses which indicated that revenue-earning capacity was improved by operating at comparatively high cruising speeds which might necessitate using up to 65 per cent. power, even though that appreciably lowered the air miles per gallon and reduced engine overhaul periods. If engines were developed to give high take-off power, should not the development also permit high cruising power? It seemed to him that if engines were capable of sustained cruising at 50 or 60 per cent. or so of their maximum output—as he suggested they should be—cruising at only 35-40 per cent. was tantamount to carrying a load of excess engine weight which, after all, did not pay any fare to the air line.

Discussing safety fuels, he pointed out that the hazard in regard to increased range of explosive fuel/air mixtures in the tanks of military aircraft with a fuel of low volatility was eliminated by the use of inert gas in the vapour space of the tanks, which he imagined should be a pre-requisite of all future military designs. In addition to preventing loss due to evaporation in flight, safety fuel would also eliminate completely the bugbear of fuel vapour locking at high altitudes or during rapid climb in very warm weather and other difficult conditions. He had been convinced for many years of the possibilities of safety fuel for reducing the fire hazard in large passenger-carrying aircraft. After all, one could not imagine the Board of Trade and Lloyds acquiescing in the use of petrol instead of heavy fuel oil for the "Queen Mary" or any other passenger liners. And, in order to dispel any rumours to the contrary, he said that high-octane safety fuels for piston engines could be made available in adequate quantities when they were required, although they would probably cost more than aviation petrol, at least until the demand assumed similar proportions.

In regard to fuels for gas turbines, he agreed fully with the author that "any old fuel" would not necessarily do. There had been rather too much tendency to assume that that was so, whereas in point of fact our present knowledge and experience of the fuel requirements of the gas turbine probably corresponded to that which existed in 1912, when the engine designers were satisfied that the only property of petrol that mattered was its specific gravity. In spite of the extensive use of oil-fired boilers for upwards of 30 years, we had still a great deal to learn about the combustion of oil and the best technique for achieving maximum efficiency.

Recalling the author's hint that the poppet

valve engine might be superior to the sleeve valve type in regard to ring gumming tendencies, he said he believed that with the use of so-called detergent type lubricating oil for sleeve valve engines, their ring gumming performance had become at least as good as that of poppet valve types using normal oil.

Finally, Mr. Ogston submitted that fuel was one of the most important single factors affecting the development of both piston engines and gas turbines. Only within the past few years had the engine builders recognised the value of taking the fuel suppliers completely into their confidence; he suggested that it would be equally in the interests of air transport operators to display similar collaboration, since it was only by complete interchange of information in respect to the effect of engine performance on operating costs that the most efficient compromises could be reached on the issue of the quality of the fuel required *versus* its cost per gallon.

Dr. S. G. Hooker : Air-Commodore Banks is in a unique position to discuss present day power plants and the trend of future power unit development. Apart from the fact that he now occupies the onerous position of Director of Engine Development at the Ministry of Aircraft Production, he has been " persona grata " at all the important aircraft engine firms in the world for many years prior to the war. He has thus had intimate contact with all shades of engineering opinion in this particular field.

The gas turbine undoubtedly possesses great advantages in the field of high speed flight, and the reasons for these are not hard to find. As a rough numerical example, let them consider a fighter aircraft which with a 1,000 h.p. engine has a sea-level speed of 300 m.p.h. Taking an airscrew efficiency of 80 per cent., they saw that the thrust on the aircraft at this speed from the 1,000 h.p. engine and propeller combination is 1,000 lbs. To double the speed of this machine at sea-level would require rather more than eight times the horse-power, in fact, considerably more than eight times the horse-power, due to the falling propeller efficiency at high Mach numbers.

On the other hand, the thrust required to double the speed of the aeroplane is only four times as great, and consequently to attain 600 m.p.h. on this machine they would require an engine propeller combination greater than 8,000 h.p. against a jet engine of roughly 4,000 lbs. thrust. Now, the weight of a piston engine per b.h.p. remains approximately constant as they increased the size. It may, in fact, tend to rise when the total installed weight is considered, so that inevitably the 8,000 h.p. engine will weigh at least eight times that of the 1,000 h.p. On the other hand, the weight of a jet engine per lb. of thrust tends to remain constant, and consequently the 4,000 lbs. thrust engine will only weigh four times that of the 1,000 lbs. thrust engine and may in fact be considerably less.

The great advantage of the jet propulsion gas turbine in the field of high speeds and high power is therefore obvious, and is in fact due to the property that the thrust h.p. of a jet engine is proportional to the forward speed. However, when coming to the turbine propeller combinations this latter advantage disappears since the power applied to the propeller obeys the same laws as that of the piston engine. With these combinations, therefore, they are thrown back on to the inherent advantages of the turbine, in their capacity for producing large powers for small bulk due to the fact that their operation is continuous rather than intermittent.

Air-Commodore Banks mentioned that gas turbines could not yet function with air fuel ratios equal to those of the piston engine, and he would like to add that the piston engine is only capable of utilising a 15 : 1 air fuel ratio because of its cyclical action. He thought that if account is taken of the air

necessary to cool the reciprocating engine its gross air fuel ratio would not be very different from that of a gas turbine, which is in fact self-cooled.

Turning now to the problem of fuel consumption, although it is true that the thermal efficiency of the jet propulsion engine does improve with altitude due to the fall in intake air temperature, yet the main reason why a jet propulsion engine becomes reasonably economical at high altitudes and high speeds is due to the fact that the aircraft requires less power to drive it at a given speed at higher altitudes due to the lower air density. For example, with jet propulsion engines the air miles per gallon will be multiplied by roughly 3.0 times between sea-level and 40,000 ft. and of this increase only approximately 20 per cent. is due to the improvement in thermal efficiency of the engine.

The gas turbine has one other advantage which helps it to excel at high altitudes, namely, its ability to cruise at powers very close to its maximum output. This feature arises from two main reasons :—

(1) The fact that the combustion temperature is reduced under cruising conditions, and

(2) The fact that the main stresses in the engine components are definite and calculable, and there are no loads corresponding to the oscillatory forces in a reciprocating engine.

The reduction of gas temperature under cruising conditions is of prime importance, because in order to obtain useful gas turbine engines it is necessary to operate them under maximum power conditions with the absolute maximum gas temperature which the materials will allow. It is a property of high temperature materials that their strength improves rapidly with a relatively small reduction in temperature, and consequently cruising and maximum conditions can be set very close to one another.

As for the future of gas turbines, it is clear also that one of the fundamental reasons for the very high fuel consumption at the moment is the comparatively low compression ratio at which they operate. More complex arrangements of staged compressors and turbines can be visualised, and with such arrangements operating compression ratio can be materially increased with a corresponding saving in fuel. As this state of affairs comes about, as come it must, one of the principal advantages of the present jet engine will be impaired, namely, its simplicity, although fortunately they have a long way to go before the complexity of a modern piston engine is equalled. D.V.

In the development of a modern piston engine one begins by attacking the larger problems. As the air becomes clearer, the multitude of small and yet vital problems which remain in any aircraft power plant become evident. Even after many years of development the sensation is that the engine is gaining on one! It may be a fool's paradise, but the opposite is the case with the gas turbine. There appear to be a few hard and difficult fundamental problems, but once these have been scotched progress is smooth and rapid.

Just as there has always been a place for liquid- and air-cooled piston engines, so he felt that the two types of turbine engine, namely, axial and centrifugal compressor types will continue for some time to come. Whereas the axial compressor offers greater compressor efficiencies, yet one must not forget the long start that the centrifugal compressor has from the mechanical point of view. The latter has a great advantage in simplicity and ruggedness of construction, and its performance is improving rapidly even though many people would regard it as dead.

Turning to the question of fuels, although one can see little use for anti-detonation additives at the present M.E.P.s of turbine engines, yet there is no reason for the fuel technologist to consider himself out of a job.

As the Air-Commodore has stated, greater calorific values per gallon are required and the field of combustion accelerators should be explored, with a view to shortening the flame length.

Lieut. S. T. Robinson, U.S.N. : It is a rare treat to have a paper containing so much factual information and so many opinions read by a person as well informed on the subject as the speaker of the evening.

The turbine engine makes a most attractive aircraft power plant due to its simplicity, smooth torque characteristics, low weight and relatively small size, but it suffers from one fault in that it is, for all practical purposes, a full throttle engine, or in terms of reciprocating engine performance there is little spread between cruising and rated powers. However, in the development of the combination he believed that advantage can be taken of the smooth torque characteristics of this type engine to give them the performance spread desired and perhaps open a new approach to the propeller design problem.

In reciprocating engine propeller applications they normally obtain about 3.5 lbs. static thrust per horse-power for use in the initial take-off run. This is at a propeller tip speed of about 1,000 feet/second. If the propeller tip speed could be increased by about 200 feet/second they would get a static thrust increase of about 2 lbs. per horse-power. Propeller structural limitations prevent them from doing this in a reciprocating engine installation, which is not the case with the turbine engine and it should be possible to overspeed the propeller in the manner mentioned for take-off.

In application this would mean that there would be a spread from 100 to 150 per cent. equivalent power between rated and take-off with the turbine engine as compared with the 100 to 115 per cent. spread normally obtainable with the reciprocating type. While it is unlikely that the turbine engine would have a lower specific consumption at cruising speeds there should not be the same relative disparity in miles per gallon of fuel due to aerodynamic improvements made possible by the smaller size and lower weight of the unit.

At the moment it looks as if in order to obtain a propeller speed at take-off adequate to attain the values of static thrust mentioned, it will be necessary to use a two-speed reduction gear. While this is departing somewhat from the inherent simplicity of the turbine engine, it does not seem to be too great a price to pay for the performance advantages obtainable.

Quite apart from this problem of application, he believed that advantage can be taken of the smooth torque characteristics of the turbine engine in both aerodynamic and structural design of propeller blades. Aerodynamically, they should be able to use thinner blade sections that might be more efficient at high Mach numbers and structurally we should be able to build lighter blading. About ten to twenty per cent. of the weight of our present propeller blades can be attributed to the necessity of taking care of unknown fatigue stresses. While the aerodynamic exciting forces will be present with either installation, there will be none from uneven torque impulses in the turbine engine. He also believed that some thought can be profitably spent on the joint between the engine and propeller, particularly if the speaker's recommendations regarding future propeller designs are followed.

In summary, the turbine engine makes possible a new approach to the propeller design and application problem and while the practicability of the weight savings mentioned must be demonstrated by vibration surveys and experience, the design possibilities are so much broader that an approach to the problem from a non-traditional point of view should result in lighter and more efficient propellers.

Lead Distribution

Mr. E. L. Bass (Fellow) (Communi-

cated) : Air-Commodore Banks has referred to the work on lead distribution. This work has given a fairly complete explanation of excessive spark plug fouling difficulties on certain engines, and has emphasised the fact that the origin of these difficulties is not so much the mal-distribution of lead as the differential distribution of lead and its associated ethylene dibromide. This has been shown by some plug fouling tests which have indicated that, if a cylinder receives twice the normal amount of lead, but with the appropriated 1 T-mix of ethylene dibromide, then the rate of lead deposition is increased by 50 per cent. If, on the other hand, a cylinder, in addition to receiving twice the normal amount of lead, receives a ½ T-mix (which is what actually happens in practice), then the rate of lead deposition is increased by 270 per cent.

It is now also clear that these lead distribution troubles are due to a small fraction of unvaporised " heavy ends " of the fuel in which an undue proportion of tetra-ethyl-lead is concentrated. Thus, manifold " drainings " show a T.E.L. concentration between 50 and 90 c.c./gal. The ethylene dibromide was, however, present in *normal quantities*, which implies a T-mix (ratio of ethylene dibromide to tetra-ethyl-lead) in these " drainings " of the order of 0.1, i.e., a tenth of what it should be. It is no wonder that cylinders receiving these " drainings " give trouble!

An incidental point of interest is that they now knew why previous attempts at carrying out spark plug fouling tests on single-cylinder units were to a large extent unsuccessful, because the lead or T-mix used did not correspond to that actually received by certain cylinders on main engines. By doing this it has been shown that rapid spark plug fouling can be reproduced in the laboratory.

It can also be stated that, in addition to lead mal-distribution being an explanation of spark plug fouling troubles, it is also responsible to a considerable extent for exhaust valve troubles. Thus cylinders receiving an excess of lead and a deficiency of ethylene dibromide will give rise to large quantities of lead oxide which will attack exhaust valves in a relatively short time.

From the standpoint of engine design, there is no doubt that, if it were possible to obviate low manifold temperatures, there would be considerable improvement. When the manifold temperature falls appreciably below 40°C., there is a very rapid deterioration in lead distribution, and it might be suggested that future designs of engine should incorporate methods of avoiding mixture temperatures below this value.

The penalty for higher mixture temperatures is, of course, some loss in cruising height at full throttle due to the reduced volumetric efficiency. The alternative solution to the distribution problem suggested by the author, fuel injection, does seem the more logical and correct one.

Safety Fuels

Our most recent experiments with injection engines and safety fuels certainly lead them to agree with the author's remark that " a good deal of work still remains to be done to evaluate the future possible use of fuels of this type."

In view of the difficulties experienced in distributing a volatile fuel, such as petrol, when using a carburettor, it is fairly obvious that with a " safety " type of fuel a different form of carburation is imperative, i.e., separate injection to each cylinder. Here, one might anticipate another kind of difficulty: safety fuels, being of low volatility, it is perhaps expecting too much to inject such a fuel at the very last moment, giving very little time for evaporation and admixture with the air.

This point has been demonstrated by experiments they had conducted in German direct injection engines (designed for aviation gasoline) which have shown appreciable loss of performance going from normal volatility

aviation gasoline to safety fuel. On one engine the change to safety fuel involved an increase of 12 per cent. in specific fuel consumption.

Their experiments have also shown that if a safety fuel is injected prior to the inlet valve, the fuel/air mixture is made more homogeneous by its passage through the inlet port; there is then little difference in the specific fuel consumption, on a weight basis, between a normal petrol and a safety fuel. Whatever difference may exist tends to disappear with increasing boost air temperature, i.e., under more favourable vaporising conditions.

There is undoubtedly a considerable field here for research and development. In many respects the problem is similar to that of the high speed compression ignition engine, viz., to find the best cylinder design, timing and positioning of the fuel injection, correct relation of atomisation and penetration of the fuel jet and the degree and type of turbulence required in the cylinder. In addition, the best inlet and exhaust valve timing will have to be determined; already our own experiments have indicated the profound effect of this upon the mixture response curve and consumption characteristics of the engine.

An incidental advantage of direct injection, which is the control over internal cooling it provides, has been demonstrated in our experiments at Thornton on German single-cylinder units. On one unit, piston crown temperatures were kept down by the fuel spray, and on another, the spark plugs were similarly cooled. The amount of spark plug cooling obtained by this means was shown by the violent pre-ignition which occurred when changing from fuel injection to normal carburation without change in load.

One advantage of safety fuel worth remembering is that, due to its higher specific gravity, its calorific value is about 5 per cent. greater on a volumetric basis than aviation gasoline.

Also, with injection engines it is reasonable to expect some improvement in smoothness of running on account of the more even impulses from cylinder to cylinder.

It is extremely difficult to assess the relative crash fire hazard of aviation gasoline and safety fuel; certainly the latter could never justify its name, but by virtue of its lower vapour pressure it may well provide just that little extra degree of safety which would save lives. Thus its use as a fuel, particularly for civil aviation, demands investigation so that the amount (if any) of the penalty in performance which might have to be paid by its use can be measured.

On the broader aspect of turbines v. piston engines, one gathers quite clearly from the paper that unless the piston engine can provide some further advantage in specific fuel consumption its days are very definitely numbered. The author has laid stress on the need to attack the problem in the piston engine by utilisation of the exhaust gas energy.

Realising the temperature limitation imposed by the turbine blades, the combination of piston engine and turbine is thermodynamically attractive. Nevertheless, it is believed that the exhaust gas temperatures of the conventional four-stroke engine are still outside the practical range of gas turbines. The two-stroke engine, as the author suggests, then becomes interesting since the use of excess air for scavenging no longer involves a total loss of energy and provides a valuable control over exhaust gas temperature. For the same reason the compression ignition engine could be used.

It would be of the greatest interest to have the author's views as to whether the compromise piston/turbine engine with its complications but low fuel consumption justifies expensive development as an interim power unit.

There is, in his opinion, one slight omission in the paper in connection with the advantages offered by the turbine in relation to the

piston engine, and that is that the turbine should not depend for its future development on the production of better and more expensive fuels. If anything, the reverse is the case and in this connection the suggestion given in the paper that additives for turbine fuels might be used is to be deplored.

Mr. J. J. Parkes (Communicated): Air-Commodore Banks raises the interesting question of the degree of noise which may be expected when the combination of propeller and gas turbine is available for use in aircraft of the future.

It may not be generally appreciated that, for this reason alone, propeller designers have deliberately selected a lower cruising helical tip speed than could be accommodated on purely aerodynamic grounds.

In the organisation with which the writer is connected, experience has shown that a helical tip speed of 850 ft./sec. has given an acceptable noise level for passenger applications, and every endeavour has been made to avoid exceeding this figure. With military aircraft it has been assumed that the same degree of comfort for the crew could not always be readily obtained and more licence has, therefore, been taken.

In comparing the piston engine propeller combination with the gas turbine propeller arrangement, it should be widely known that, in the former, a reduction of something like 40 per cent. on take-off r.p.m. can be obtained with good cruising efficiency; whereas, in the alternative system, this figure will probably be only 5-10 per cent. Piston engines have been developed to give high take-off r.p.m. at reduced m.e.p. and to cruise at a low r.p.m. and high m.e.p. in order to get the best of both worlds. In other words, the high take-off r.p.m. has not been developed only with the idea of power output, but in order to obtain high thrust figures at low blade angles.

As Air-Commodore Banks says, the propeller turbine combination may be noisier because this degree of flexibility will not be available and the cruising condition cannot be remedied by a revision of gear ratio due to the impossibility of obtaining a satisfactory take-off condition, which is the very place where the propeller part of the combination is expected to provide one of its biggest contributions.

Dealing with the entire question of passenger noise, it is felt that this subject presents a field in which there is scope for a very considerable amount of valuable research—for example, it is known that the division between an impression of noise or annoyance detected by the organs of hearing is not very clearly separated from sensory impressions received as vibration by portions of the body in contact with the seat and floor of the aircraft.

The introduction of shock-absorbing material to the floor, and well insulated seating will actually convey an impression of noise reduction and for passenger aircraft it is suggested that some specialised work in this direction would be of considerable value. Furthermore, the whole question of noise should be the subject of careful analysis and overall noise measurement is not a suitable comparison or index. It is desirable, in reviewing a given noise level, to consider its frequency composition. A predominance in the lower frequency spectrum is generally found to be more fatiguing, whilst marked attenuation in the higher frequency spectrum is usually easier of achievement.

In comparing piston engines and gas turbines, it is of interest to note that the vibration frequencies principally encountered in the former fall generally at the lower end of and below the audio-range, whilst experience has already shown that the gas turbine produces vibration of a supersonic frequency.

From the foregoing, it can be concluded that investigation of vibration damping and noise reduction, and the impression of fatigue and annoyance produced by both, must extend from sub to supersonic frequencies.

A great deal of useful work has been done on noise reduction in test houses, and now is the time for the subject to be tackled on a scientific basis in the aircraft itself.

Mr. A. V. CLEAVER (Communicated): The lecturer's views on requirements for future propellers will meet with little disagreement; in particular, the independence of the propeller pitch change mechanism from the engine is most desirable. To some it may seem that the converse should be true, and the propeller and engine should be designed as a complete unit, having much of the pitch change mechanism built into the engine nose. This might be the ideal theoretical solution, but in practice, with separate firms producing engine and propeller, a trend towards complete independence is more logical, with each organisation responsible for satisfying its own requirements without embarrassment to the other.

It was surprising to find so little reference in this paper to the large possibilities offered by braking propellers, for landing, as air brakes, and for ground or water manœuvring. In some cases its ability to provide these features may be one of the biggest advantages the propeller can offer against the pure jet or the ducted fan.

Air-Commodore Banks' statement (during the discussion) that propeller propulsive efficiencies of 70 per cent. should be attainable at top speeds of 500 m.p.h. is entirely reasonable, but it might be disputed that this is not " a serious drop in their efficiency." Certainly, by 550 m.p.h. it seems very doubtful whether the propeller should be regarded as a legitimate competitor of the jet, which shows so many other advantages of lightness, simplicity, and compactness of installation, all tending to favour its introduction before that might be expected from considerations of efficiency alone.

Perhaps the small diameter ducted fan may be the ultimate compromise answer for this top speed régime for longer range aircraft. It sets out to attain the best of both worlds, but it seems possible that it may do exactly the opposite, and fail, if it is regarded as an ancillary rather than as an integral part of the unit, by having the disadvantages rather than otherwise of both propeller and jet. However, jet unit layouts will probably develop in which the initial low pressure compressor stages are indistinguishable from a fan thrust augmenter.

Few will dispute that the simple jet is the answer for the Spitfires and Mosquitoes of the post-war generation of aircraft. Equally, at any rate, the first purely post-war generation of heavy bombers and airliners should surely use turbine driven propellers. Whether this condition endures, or the jet eventually takes over this field also, is almost entirely in the hands of the aircraft designer. It is a question of operating conditions and aircraft characteristics under his control rather than the power plant designer's.

Many speakers in the discussion stressed the need for greater enterprise and originality in aircraft layout and design generally. This seems justified in view of the stereotyped character of aircraft design for the last ten years. Perhaps the large blower of the jet or propeller turbine unit may encourage the study of boundary layer control possibilities of higher maximum lift coefficients and consequent higher loadings, and of reduced low and high speed drags.

In any case the turbine propeller combination has many interesting possibilities, and it seems almost certain that, even looking very far ahead, there will always be a class of slower aircraft employing this power plant type. Turbine propellers should be appreciably lighter than those for piston engines of similar power, due to reduced vibration excitation. Detail design problems of governing, etc., will be introduced, and there will be a particularly good case for two-speed reduction gears to make efficient use of the high take-off power of the turbine at

sea-level, relative to its cruising power at altitude. The case is accentuated by the very small percentage change in r.p.m. rating of the turbine between cruising and take-off. This, as the lecturer implies, will lead to noise difficulties with a single compromise gear, but a two-speed gear would help in this question also.

The very high thrust possible with a two-speed gear on a turbine propeller of high take-off power should encourage the use of aircraft of higher loadings cruising nearer to maximum L/D conditions, at higher power outputs, with consequent benefit to the turbine specific fuel consumption. The unassisted take-off run should still be acceptable, and the landing run would also be with braking propellers.

Mr. P. G. Lucas (Associate Fellow) (Communicated): He would like to lay emphasis on the importance of flight testing during the development life of a power unit.

During his fairly comprehensive experience on the development of fighter aircraft, he would say without hesitation that 75 per cent. of all prototype flying is taken up with the development of the power unit and its installation, with the result that the flight development of the airframe is often held up pending the over-riding necessity of obtaining a reliable power unit first.

Even with the orthodox engine, ground tests have been proved to be inadequate in representing flight conditions, for apart from normal installation problems, such things as carburation, supercharging, distribution, ignition and oil circulation can seriously influence the mechanical reliability and functioning of the power unit. With the greater speed and altitude possibilities of turbines it will be even more difficult to represent flight conditions on the test bed.

As the lecturer points out, the tendency is for turbine power units to be tailored into the airframe, and this will become of greater importance as speeds increase. Flight development, therefore, will not only become even more necessary than before, but in the case of prototypes, more the obligation of the airframe manufacturer.

The whole project calls for a greater number of prototypes so that separate problems can be tackled in a logical way without upsetting the development programme of all the others, also for very much stronger technical teams of trained power installation engineers.

In his opinion it is the lack of these trained men, the lack of appreciation of the importance of flight testing, and the lack of facilities for tackling obscure and urgent problems which have been responsible for the appalling list of troubles shown up during the initial stages of testing prototypes, and the length of time taken in solving them.

Mr. D. R. Pobjoy (Communicated): Several speakers emphasised the importance of fuel consumption in terms of brake horse-power. But such figures by themselves applied to an aircraft engine have but little meaning. The important criterion is the relation between the net push given to the aircraft (i.e., the thrust horse-power after deducting external and cooling drags, propeller losses, etc.) divided by the total weight of the power unit including the fuel, oil and tanks. The resulting figure of merit should be assessed for the three régimes of take-off, all-out level and cruising at rated altitude.

By this simple criterion, the relative merits of the various systems of propulsion and power generation may be determined and fields of application chosen to suit.

Alternatives may appear. For instance, an aircraft could have an extravagant light engine, or an economical heavy one. An extreme example is the V.1 flying bomb—all fuel and (almost) no engine. The addition of a normal piston engine and propeller to this machine would save $\frac{7}{8}$ths of the fuel, but the weight of the additional plant would just

counterbalance the saving, leaving the figure of merit the same.

For commercial aircraft the cost of the equipment and of its operation and maintenance must be considered. These are, however, of secondary importance because they affect the costs of the power plant only while the weight of the latter, by affecting the pay load, influences the total operational costs of the aircraft.

Other considerations are :—

Jet propulsive efficiency increases with speed, while that of the propeller falls off.

As the altitude increases, the lower air temperatures permit a turbine engine to work at increasing temperature ranges resulting in improved thermal efficiency. That of piston engines does not so increase unless they are compounded with exhaust turbines.

Phenomenally low brake fuel consumption could certainly be obtained at, say, 20,000 ft. from the heavily supercharged two-stroke Diesel engine/turbine combination mentioned by several speakers. But whether its extra weight will be justified by its fuel economy depends upon the range of the aircraft, or rather its duration. Lindbergh took 42 hours to fly from St. Louis to Paris, and his fuel consumption was of extreme importance. If, as seems likely, flights in the future may be limited to eight hours, fuel economy may prove less important than saving in power plant weight. I should like the author's views on normal maximum flight periods for commercial aircraft in the future.

A further aspect is the scale effect. Little reciprocators are easy to make, large ones are progressively difficult. On the other hand, if they ask a turbine man to make a 10 h.p. unit he would shrink from the difficulties, weight and complication; while for a 100,000 h.p. unit he would just reach for a reference book and read out the general dimensions.

Moreover, turbine engines are inferior to piston engines from two aspects usually glossed over: excessive fuel consumption at part load and loss of power at high atmospheric temperatures. The piston engine is usually set to be extravagant during take-off, but to be economical when it matters, that is, while cruising. Unfortunately it is not easy to arrange this with turbine engines without additional complications.

He noticed that the author states that the simple jet engine is about $\frac{1}{3}$rd the weight of the piston engine, power for power. All-out level power, not take-off power, is meant he supposed, otherwise the proportions should be reversed. And take-off must be coped with.

The air consumptions of piston engines and propeller/turbine engines are broadly similar, except that only about 15 per cent. actually goes through the piston engine, the remainder being used for external cooling: while the whole of the air goes through the turbine engine. The residual pressure and velocity of the vitiated cooling air render it less suitable for jet propulsion than the turbine efflux. In a fast aircraft the last ounce of energy need not therefore be extracted by mechanical means from the turbine efflux. In a slower machine it will be necessary to have many turbine stages to extract the maximum possible energy. For low and slow aircraft enough stages should be provided to leave the exhaust only with sufficient energy to push it around a heat-exchanger. In other words, the problem of a surface or marine installation.

Examined in this way, appropriate fields of application of the various types might be :

(1) For ultra-high speed at ultra-high altitudes, the turbine-operated jet should be unrivalled.

(2) For high speed at high altitudes and large powers, the propeller/turbine with plenty of jet should be paramount.

(3) For moderate speed at high altitudes and moderate powers, heavily compounded piston engines may have advantages over multi-staged turbines.

(4) For moderate speed at low to moderate altitudes and moderate powers, the multi-stage turbine engine with heat exchangers will compete with the piston engine with single-stage single-speed blower.

(5) For low altitude, low speed and power, the simple piston engine will probably always have a place.

In regard to the specific output of piston engines, he noticed the author cites the power per sq. inch of piston as the criterion of performance. This is much the same as heat flow per sq. inch of piston and cylinder wall and is certainly a criterion of engine quality. But the aircraft designer is more interested in power per cubic inch because the swept volume is more nearly related to the engine weight and bulk than is the piston area. If cooling fins and sparking plugs could be scaled down exactly, air-cooled cylinders of every size could be made to develop the same h.p. per sq. inch, but their power per cubic inch would vary inversely as the scale. In practice the small cylinder is handicapped by the difficulty of getting fins and plugs on the head. The liquid-cooled cylinder is not so seriously handicapped in this way, so that there is a case for a large number of small liquid-cooled cylinders or a smaller number of large air cooled cylinders. Suitable geometrical arrangements may be left to the imagination bearing in mind the criterion of net thrust h.p./all-up weight.

In regard to so-called safety fuels fed to piston engines by direct injection, would the author please confirm that one of their less advertised advantages is the reduction in risk of vapour locks in the fuel system in hot weather or on elevated airfields.

Squadron-Leader D. G. SAMARAS, R.C.A.F. (Associate Fellow): It is regretted that "much ado about nothing" has been created by the so-called super-optimists and sub-pessimists. The present writer working for the last six years on aircraft gas turbines is of the opinion that every type of engine has its own field of application. It is a pity that for security reasons he was not allowed to quote any figures from his own work; moreover, he was quite convinced that both the above mentioned rival parties having access to it would form a better picture of the future development.

Generally speaking, without any prejudice or preconceived ideas they could state that for low altitudes, powers and speeds the reciprocating engine is well established. For higher power and altitudes, and up to speeds of, say, 500 m.p.h., the propeller gas turbine is supreme. Above that, the Whittle type simple jet and the axial flow type have their own range of operation. Above 1,000 m.p.h. (for the sake of argument) rockets for interplanetary transport would be used. There is a wide range of speeds which two rival power plants would claim as their own, though it is felt that an intelligent compromise will sometimes give the best answer. For example, when they reach the stage of supersonic flight they might well use jettisoned propulsive ducts in conjunction with rockets to be put into operation in the lower layers of the atmosphere.

They had to thank the author, who as a fuel specialist disproved the widespread fallacy that the price of the gas turbine fuel is going to decrease after the war.

The author claims that:—

"In addition to the various methods mentioned here for improving the *operating economy* of the turbine, there is very close collaboration with the material suppliers to give us improved materials—for blades, etc. —which will allow higher operating temperatures and so further improve the *thermal efficiency*."

Again, from the remarks made by Dr. Ricardo and A.-C. Whittle, the wrong impression was left that by increasing the maximum temperature of the cycle a better specific fuel consumption (lb. of fuel per lb. of thrust) would result. This is not true for

the simple jet gas turbines (especially those of the Whittle type at subsonic speeds) because the propulsive efficiency is rapidly decreasing with increasing maximum temperature, and it can be safely stated that the engines flying to-day have already exceeded the optimum maximum temperature by some hundreds of degrees. This is not so for the propeller turbines, because in these, both the specific fuel consumption and the specific output improve with an increase of the maximum temperature.

Regarding the employment of mixed compressors in a unit (axial + centrifugal) it is felt that great caution is required in adopting such combinations because the resulting power plant inherits most of the disadvantages of the parent power plants, and the resulting complications would be rather disappointing.

As for the great decrease in time for design and development, it is felt that the author is rather exaggerating the difference, at least for the propeller gas turbine case.

It has to be remembered that the matching of multiple turbines, compressors, combustion chambers, propellers and exhaust systems is not an easy task, especially if we want efficient running over a reasonably wide range, free from surging, choking and other troubles.

Finally, it is felt that further research to obtain the scientific data lacking to-day will enable us to replace the present semi-empirical and intuitive methods of design, and will result in high performance and scientifically sound power plants.

Mr. A. W. Morley (Royal Aircraft Establishment, Associate Fellow): From the paper they had just heard it does appear that they may confidently expect gas turbine engines to hold the field among large power plants in the not too far distant future. Plain piston units will probably never exceed the 6,000 b.h.p. size because such a size could only be reached by a slow process of development and at the expense of multiplying the number of cylinders, a method which few designers support with enthusiasm. At the small end of the size scale the gas turbine engine has fewer possibilities. On the basis of efficiency alone the piston engine is likely to be supreme for some years for powers of about 500 at take-off and below.

The range of power unit from 500 to 6,000 b.h.p. admittedly extrapolated at the upper end, surely covers very many aircraft, military and civil. Conditions are wholly in favour of the piston engine at the low end of the scale; the gas turbine engines will claim an increasing share of the upper end.

It is obvious, he thought, that the reciprocating engine is in a strong position for powers even considerably above the 500 h.p. mark. This is predominantly the field of civil aviation where the natural economic factors are more or less established on the reliable basis of the reciprocating engine.

He agreed with the author that the simple jet gas turbine power plant is predominant as the future power plant for military requirements of high-speed flight. As an offensive weapon it is liable to be superseded in its turn. They had seen one serious challenger already in the field. In any case, its efficient use for long ranges demands difficult improvement in aerodynamic technique.

The gas turbine is novel and stimulating. It has several extremely valuable advantages to offer where the reciprocating engine labours under difficulties. It is rightly a research item of intense importance. We must remember, however, that it is mainly in research for military purposes where the interest lies. It remains to be seen whether all things considered it will provide them with an economic type of power plant from the civil point of view. They still have to prove that its operating life can be made sufficient in terms of cost, and further, that aeroplane design, which involves many factors, will lend itself to turbine development to the full extent expected.

Many people believe that the propeller turbine should be the main line of development. The chief advantages which, in the main, are still only predicted advantages according to calculation, result from its low weight and compact size, its reduced fuel consumption at high altitudes and high forward speeds and a flexibility in performance which allows it to be used economically at speeds well above the minimum drag speed of the aircraft. Its disadvantages are the propeller and gearing, the more complicated turbine, the control problem and the thermodynamic disadvantage of decreased efficiency at partial load. On the basis of power plant weight plus fuel weight, careful calculations show the advantage of such an engine over the simple jet type, except for very short flights. However, the present gas turbine development started with the simple jet and it seemed to him that it is bound to be more concentrated on the simple jet for some time to come; and because of the inherent simplicity of such an engine it will be applied to aircraft well beyond the stage where it would pay to develop a propeller turbine instead. The efficient propeller turbine of moderate output is essentially a further step in gas turbine practice. He felt, therefore, that although on thermodynamic grounds it is the most serious competitor the reciprocating unit has to face for aircraft carrying a heavy pay load over long distances, it will not be a pressing competitor for some time to come.

It seemed to him that although the period of exciting research has passed, they have still a great interest in the development of piston-type engines, especially in the small and moderate sizes. In particular they should continue to develop the technique of air cooling as well as the features which effect better fuel economy, better serviceability, lower specific weight at take-off, and, above all, improved safety. The jet engines have already focused attention on the vital importance of engine weight in relation to fuel consumption, and also the essential need to make the utmost use of the exhaust gases.

In the piston engine world the development of anti-knock fuel is essential in order that engines may be up-rated to produce the power which they are well able to withstand for short periods. The gas turbine does not call for the same up-grading of fuels. This seemed to him a crucial issue; will the high anti-knock fuels be readily available for the piston engine? The gas turbine has material problems. He who would predict far into the future must weigh up the relative efforts of the fuel industry on the one hand, and metallurgists on the other; and further, fully appreciate aerodynamic and economic improvements, since it is also necessary to predict the trends in top speed and cruising speeds of aircraft.

It is true, as Air Commodore Whittle has said, that an increase in aircraft speed will appreciably increase the power of gas turbine engine more than it does for the piston engine without any work on the part of the engine designer. Vice versa, and more commonly, a loss in the aircraft design speed will subtract appreciable power from the engine without the designer being able to avoid it.

Mr. A. S. HARTSHORN (Royal Aircraft Establishment) (contributed): Both the lecturer and subsequent speakers have shown the difficulty of comparing the performance of a piston engine with that of a gas turbine. This difficulty is fundamental and may demand an entirely different approach in assessing the performance characteristics of an aero engine. Various aspects of this difficulty are itemised below.

(i) One point brought out is that in comparing weights it is engine weight plus fuel for a given range which counts. This weight should be the overall installation weight which includes the increased structure weight necessary to carry the engine and fuel.

(ii) Another point mentioned, but on which attention was not directly focused, is that

the piston engine performance is quoted in torque power, whereas the turbine performance is quoted as thrust. Thus the inefficiency of the propeller (which may be considerable at high speeds) should be charged up to the piston engine.

(iii) Both types of engine need cooling; with the turbine excess air is pumped through the engine and the work entailed in this is deducted from the accredited power output. On the other hand, the piston engine gets off scot free; the cost of cooling is charged up as an airframe drag. The item is serious enough to merit attention—whilst the published pre-war figure for cooling was about $2\frac{1}{2}$ per cent. of the b.h.p., present day high performance military engines with cooling adequate for tropical conditions use considerably more than this, and a figure of 10 per cent. is probably nearer the truth. (Digressing for a moment, the cost of charge cooling is particularly high because for indirect cooling the available temperature difference between coolant and air is small, and for direct cooling the ducting is difficult.)

(iv) Drag should also include the drag of the engine housing. This item is probably not very different for the two types of engine, and for a high-speed twin-engined aeroplane it should account for 10 to 15 per cent. of the gross engine power.

(v) The total installation drag will also include certain other effects such as interference and the possibility of using low drag wing sections. Thus a particular engine may have a greater economy when used as a pusher than when used as a tractor; similarly, the jet engine will have a potential advantage over one with a tractor propeller.

(vi) The above items favour the turbine type, but it must not be forgotten that the piston engine can provide a useful amount of direct thrust from the exhaust, especially if night visibility is no objection.

These remarks state a problem, but do not indicate any solution. It may be that the only real method of comparison is by application to a specific design, and, as has been stated by Air Commodore Whittle, this may lead to unsuspected answers.

Mr. H. SAMMONS (contributed): As far as civil aviation is concerned, there are two aspects of aircraft development in the future on which too much study and research cannot be applied, namely, safety and economy.

Economy.—In his opinion this can best be served by reductions in maintenance and fuel costs. It is possible that the turbine will automatically produce the desired improvement in maintenance cost, but care must be taken to see that in striving for fuel economy over wide operating conditions the turbine plant does not become so complicated that maintenance costs are increased. It may well be that the efficient combination of the two-stroke cycle piston engine with the gas turbine will play an important part due to the very high thermal efficiency which such a combination makes possible. As far as civil aviation is concerned, every effort should be made to economise in operational costs so as to avoid the necessity for State subsidies, in order to make their commercial operation successful.

Safety.—It is difficult to appreciate that aviation can assume its rightful place in the affairs of the world until accidents are reduced to a smaller proportion than has been the case in the past. Although statistics may show that the accident rate per passenger-mile flown is very good, every single aircraft accident, whether it be military or civil, if publicised, will have a detrimental effect upon the general public's desire to use aviation as their mode of transport. Therefore, any development which will reduce the fire risk, or increase the mechanical reliability of the power unit, should take a high priority in the post-war development plans. There is no doubt that the advent of the turbine, either alone or in combination with the piston engine, has great potentialities for making flying even safer than it has been in the past.

Mr. J. AHERNE HERON (communicated): From the lecture one might gather that the gas turbine may or may not be too far off. Therefore, should one wait till it is in a more advanced stage before attempting commercial editions, or is the gas turbine so near now that work on further development of two-stroke diesels and improvements on normal internal combustion is unjustified? Is it worth while the airscrew people attempting to make hollow steel blades at this stage, or should they turn their energies to ducted fans and axial flow compressors? With regard to this latter point, he did not agree that hollow steel blades will be worth while, as the thickness-chord ratio, together with the pitch diameter that will be required for later high-speed craft, does not appear to justify the small amount of material that it will be possible to remove, especially if the inner half of the blade may be used for the first stage compression for the compressor, and the outer portion as the normal airscrew.

How right Air-Commodore Whittle is to plead for attempts to keep the gas turbine simple, and not stick an up and downer in front of it, merely to find work for that out-of-date industry. It is obvious that not only are there a limited number of thought-hours available for development, but man-hours also, and it is felt that they should be concentrated on solving the basic problem which tends to simplify the unit rather than complicate it. By this it is meant that these thought- and man-hours should be spent in finding a solution to running the turbine at these higher temperatures, rather than introducing a mechanically inefficient unit on the front to do this work. If the same amount of resources that may be diverted to trying to make this a solution were put into the development of materials and cooling techniques, it is felt that a more speedy and efficient solution would be found.

More work should be concentrated on blade cooling and the introduction of lubricants on the surface of the blades to keep them cooler, even if this lubricant was only cold, secondary air.

With regard to materials, it is felt that powder metallurgy ceramics, super-purity materials, would all justify a complete investigation, as it tackles the basic problem, and not superficialities.

Mr. J. LOWREY (communicated): He would like to comment on the statement that "A strict timetable should be adhered to for the development programme." This dictum will undoubtedly be approved by production executives, but is surely incompatible with true progress.

When a successful engine is already in production, and work on detail improvement is in hand, imposition of a timetable is reasonable. No objection can be raised in this case to the fixing of a date by which development engineers must have ready any improvements to be incorporated in a forthcoming engine "mark."

In the initial development of a new engine type, however, he would regard adherence to a strict timetable as intolerable. Such work inevitably involves groping into the unknown, and while it may be sound psychology to publish a timetable, over-strict enforcement of it may lead to production effort being wasted on an unsatisfactory, even unsafe, power unit.

Secondly, he was surprised that no mention was made of the compression ignition engine, save as a possible high-pressure stage in composite reciprocating-turbine power units.

Air-Commodore Banks states that in the future the piston engine's principal claim for remaining will be its cruising fuel consumption. Although, during the 1920s, Dr. Ricardo concluded that there was little future for the compression ignition aero engine, the writer was doubtful if his conclusions remain valid to-day.

It is commonly argued that modern fuels permit the petrol engine to operate at such low specific consumptions as to render the

C.I. engine inferior in engine-plus-fuel weight for even the longest flights. Full allowance is not always made, however, for the fact that under operating conditions the C.I. engine approaches much more closely to its ideal test bed consumptions than does the petrol engine. Improved carburation may widen the range of powers over which a petrol engine can operate really economically, but the full throttle engine seems bound to retain an advantage over the throttle controlled type.

With modern developments of power boosting and of assisted take-off, he believed that there are wide fields of use for compression ignition engines. In fact, it seems probable that the turbine engine will eventually be adopted for short flights, and the compression ignition reciprocating engine for long flights, the petrol engine being of questionable advantage for medium distances only.

Group-Captain A. F. SCROGGS (contributed): Although the lecturer emphasised that his paper dealt with power *units* rather than with power *plants*, he most heartily agreed with Group-Captain Bulman that the two must be considered together, and their development must proceed side by side and with the closest co-operation between their respective designers. It would be safe to say that the great majority of troubles in new types of aircraft in the past have been due not to the airframe itself, nor to the engine itself, but to the engine installation.

It seemed to him that there is a general tendency to treat the power unit merely as a device for converting chemical energy of fuel into mechanical work, rather than as a part of an aircraft. It is all very well to talk of power per sq. in. of piston area, or lbs./b.h.p.-hr., as a measure of the merits of a design; but these are not in themselves of the slightest interest to the operator. What ultimately matters is the performance and range of the *aircraft*. Air-Commodore Whittle made this point in connection with gas turbines, but the same also applies as between different piston engines.

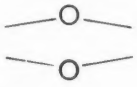
Too little regard has been paid in the past to maintenance and reliability. The former is largely a matter of design and calls for careful thought and foresight at an early stage; the latter demands long development and thorough testing—especially flight testing. The requirements of Civil and Service engines are somewhat different for whereas both need the utmost reliability, the Civil engine can expect a high degree of skill and elaborate equipment for maintenance, the Service type in wartime must be maintained by butchers, bakers and basketmakers working against time and often in the most appalling conditions. It must never be forgotten that their effective strength of aircraft is not the total number they possessed, but the number that can be kept serviceable —a distressingly small proportion of the total, depending directly on ease of maintenance. To the nation this means using up the available production capacity; to the civil operator it is a matter of idle capital and swollen pay-rolls.

The need for reliability should be obvious, but it still does not seem to be taken seriously enough. He would like to see every designer and development engineer compelled to undertake a flight with his engines over the sea, preferably in bad weather and without radio, in a single-engined aircraft or a twin that will not keep in the air on one. He had done a lot of this himself and it makes one think. Personally, he was in favour of air cooling, especially for long-range service aircraft. He did not say that an air-cooled engine is inherently more reliable than a liquid-cooled one, and plumbing seems to be better than it was, but there is always the chance of a bullet or a piece of flak in a tender part of the cooling system, and even a small leak can destroy a whole aircraft and its crew.

Engine design is a mass of compromises, and it is not possible to provide all the qualities desired in full measure. For some pur-

poses it may be necessary to sacrifice other qualities for high performance. He thought different types should be developed for different applications as the high-performance engine does not always give greater reliability or durability when de-tuned, and vice versa. The Americans have had considerable success in " hotting up " engines once intended for airline use; it remains to be seen whether we can do better still by the reverse process.

He was pleased to see several references to two-strokes. He had always felt that this fascinating line of development has been too long neglected. Whether it is now possible, or worth while, to make up for lost time, he did not know; but the supercharged, fuel-injection two-stroke with a rotary or sleeve valve (preferably the former) offers great attractions. He would venture to suggest, as a simple, neat and compact layout, a 24-cylinder two-crankshaft engine with banks at 150° to each other, thus:—



REPLY TO DISCUSSION

Air-Commodore BANKS: He thanked Dr. Ricardo for opening the discussion, and for his valuable contribution to it. He was glad to have the confirmation of one in Dr. Ricardo's unique position, on the future of the aviation engine.

Undoubtedly piston engines would still be seen in aircraft ten years from now, but the gas turbine would, he thought, eventually oust the piston engine for many applications. One thing which would help to kill the piston engine more quickly, particularly for transport purposes, was vibration. Anyone who had flown in a turbine engined aircraft would never wish to fly in one with piston engines again. In other words, a large proportion of passengers would be prepared to pay higher fare rates for the relative comfort, restfulness and speed which should be the outstanding features of turbine engined aircraft. And the transport operators would have to meet this demand, which might override, to a large extent, the disadvantages of the high relative fuel consumption of the gas turbine.

For military machines, where long range at low altitudes or long duration were the requirements, then he thought that the combination of either the petrol or the compression ignition two-stroke engine and the gas turbine would be the power unit to go for. Dr. Ricardo can be credited with the original suggestion of such a power unit.

It was his, the author's, opinion that this would be the only practical way of applying a compression ignition heavy oil engine to aviation purposes. The normal four-stroke compression ignition engine had never been worth while developing as an aviation power unit, since it only burned about 80 per cent. of the air which it took into its cylinders, and therefore was always at a disadvantage relative to the four-stroke petrol engine. This feature gave it (the C.I. engine) a lower take-off to cruising power ratio and made it a heavier job than the petrol engine.

Such was also the case with the two-stroke C.I. engine—that it would only burn about 80 per cent. of the air in its cylinders—but by using the two-stroke as a gas generator and with the large amount of gas and heat energy issuing from its exhaust, it was a very attractive proposition when linked up with the turbine.

The Author was glad to have Air-Commodore Whittle's amplification of the point he made, in the paper, regarding temperature reduction with height and its effect upon improving gas turbine efficiency.

Air-Commodore Whittle's point on the effect of aircraft drag was, to his mind, most important. And this was so for another reason. In the case of the simple jet and, for that matter, the propeller/turbine, the cruising power would not be much below full power and therefore the cruising speeds of turbine engined aircraft would be much

nearer their top speeds than was the case with piston engine installations. The necessity, therefore, for making a clean airframe was absolutely vital.

In regard to propeller efficiency, Air-Commodore Banks was hoping for about 70 per cent. at speeds up to 500 m.p.h.

The author still felt that the present high specific fuel consumption of the gas turbine was the one bar to its almost universal use in aircraft; and although he knew that Air-Commodore Whittle disliked " this up-and-down piston engine business," he felt that the piston engine would still be in the picture for some time to come, even although he agreed that it might be used in combination with the turbine. There would be many cases where it would be necessary to operate aircraft at altitudes lower than, say, 20,000 feet, and they would have to see much higher fuel economy from the gas turbine if it were to compete successfully with the piston engine at such altitudes and for reasonably long ranges.

In reply to Mr. Rowe, he was very gratified to have someone with Mr. Rowe's wide experience of aircraft and aerodynamic problems as a contributor to the discussion.

As Mr. Rowe had mentioned, the paper was designed to review the engine position as it stood to-day and to give some idea of what the future held. He had purposely written the paper along different lines to those usually read before the Society since, as Mr. Rowe had inferred, it would not have been possible to publish any data of real interest at this time. But the author felt that what was wanted now was some definite information and even provocative statements of a specific nature which would give some idea of the direction in which we were heading in aviation during the next decade. The paper was written to promote discussion along these lines, since the author had always felt that a paper was only as good as the discussion it promoted.

Mr. Rowe's contribution brought out some very valuable points, and if the present " tribal squabble " were to be quickly ended, then the author felt he could give Mr. Rowe a reasonable assurance that the ordinary piston engine could be developed to give a cruising fuel consumption of 0.40 lb. per b.h.p.-hr. and 750 hrs. between overhauls—possibly 1,000 hrs.—in five years' time. All this without reducing the high take-off power, which was now being used for heavily laden bombers.

Mr. Rowe's point regarding fuel economy and its effect on the size of aircraft had been little appreciated in the past, but it was one of the most valuable points mentioned that evening.

He was very interested in Mr. Rowe's views on clean wings and their structure weight for fast aircraft. But he still thought that for extreme speeds up to, say, 600 to 650 m.p.h. it would be necessary to have a wing thickness of not more than 10 per cent. at the root and he felt that this would inevitably lead to wings of more massive structure. But this would not necessarily be a disadvantage to the aircraft as a whole. For future fighter aircraft of these speeds, however, it would not be possible to put any fuel or guns in the wings. All these would have to be accommodated in the fuselage.

Mr. Rowe apparently did not agree that there was a " compressibility wall," and the author was interested in his analogy. Mr. Rowe's analogy was very apt if one were a mountaineer, but the author was not and he felt that it might not be a correct one because he thought the compressibility problem, although not insuperable, was then similar (still taking Mr. Rowe's analogy) to scaling Mount Everest, which had not yet been done by any human being.

He still felt that there was a " compressibility wall " and that a more true analogy would be that of a tank rolling up to a concrete defence barrier and then having to exert extreme power to push it over—after which the tank could continue on its course. Similarly, the aircraft to reach a Mach number

of one and go just beyond it would, so far as the author understood, require approximately six times the engine power that would be necessary for Mach numbers below unity.

On the question of engine size and number, he felt that if it were necessary, as Mr. Rowe suggested, to keep to the minimum number of propeller discs along the wing, then engines of reasonable size could be installed in the wing in multiples of two, driving co-axial counter rotating propellers through a gearbox.

On the question of fuel supplies, raised by Mr. Rowe in the latter part of his discussion, he thought it would not be economical to use coal resources for the production of fuel for either petrol or turbine engines. It was still more economical from a cost and quantity point of view to import oil from those countries where it came from the ground in its natural form; and it was also cheaper to process crude oil than coal.

He did not agree with Grp.-Capt. Bulman that he was a super-optimist, nor did he agree that his statements on the gas turbine were day-dreams. If one were not enthusiastic and not convinced that a new prime mover such as the gas turbine was a practical proposition, they would not have got so far as they had, to date. Even now and with their apparent lack of knowledge and experience of gas turbines, relative to piston engines, the simplest form of gas turbine could confidently be designed and would work quite satisfactorily in fighter type aircraft.

The author, therefore, was somewhat worried that Group-Captain Bulman still remained piston-engine-minded; particularly since the author regarded him as one of the few people in this world who could rightfully be called an "expert." Group-Captain Bulman was an expert on the development of fighter aircraft and their engine installations, and this was the type of aircraft in which the gas turbine could replace the piston engine almost immediately.

The author agreed whole-heartedly with Group-Captain Bulman when he said that "one ounce of development in the early stages was worth thousands of pounds in the post-design or production stages."

The author meant what he said in his title —"power unit," not "power plant." He agreed that the engineering of the power plant was most essential and had been neglected in the past. But one had to have the power unit first, and it was this that he was discussing in his paper. Any experienced engine designer to-day should and would take account of the installation of his engine in an aircraft. But the design of an entirely new engine, with little previous background, could not, in the design stages, be entirely prejudiced by installation problems. The engine must be made to work first.

The author could not agree with Group-Captain Bulman that the gas turbine in its present form was as undeveloped as the early rotary engine. So far, they had only two or three years of relatively intensive development of the gas turbine, and yet, during this time, a particular gas turbine had been designed, built and run, all within six months; and had already shown that it was capable of running 100 hours. Another similar turbine had recently passed the official 100 hours' type test. The rotary engine in its early stages could not have looked at these running hours or passed any test half so severe as the present type test. The rotary engine was doing very well if it managed to last 20 hours and, in its later stages of development, 80 to 100 hours.

In reply to Dr. Roxbee Cox, he was glad to have his views on the vexed question of the relationship of research and development. As the author saw it, the pure research worker was a man who had been given the best theoretical education possible, to qualify him in his investigations to establish certain fundamental laws or data on a given problem or subject; and, therefore, to

be able to explain certain phenomena. The development man was one who had to gain a considerable experience of his job, which was really in the nature of skilled " cut and try." In the case of engines as distinct from atoms and " atom splitting," the author felt that there was little or no line of demarcation between research and development. But development was quite exciting, all the same.

He agreed with Dr. Roxbee Cox that it was dangerous to consider the fuel economy of a gas turbine on the basis of lbs./thrust h.p./hr., or lbs./brake h.p./hr., and fuel economy, particularly in the case of gas turbines, could only be evaluated in flight on an " air miles per gallon " basis. But the test bed figures had some relationship between engines when new designs were being considered and developed.

He agreed with many of the remarks Mr. Tresillian made on poppet *versus* sleeve valves. But he felt that each had its place, although in his opinion the only advantage the sleeve valve offered was that of a better geometrical layout, particularly in the case of large engines.

He did not necessarily agree with Mr. Tresillian that there was an advantage in raising the piston speed above the figure (3,250 ft. per min.) he had given in his paper. This appeared to be an optimum figure so far as mechanical efficiency, oil consumption and compactness of the engine, as a whole, were concerned. In the case of a short-stroke engine which had to run at high crankshaft speeds in order to approach the piston speed quoted, it was always more difficult to control the oil consumption, which rose with speed somewhat as surtax increased after a certain salary figure had been reached.

He agreed with Mr. Tresillian that a lot could be done with various forms of cylinder and cylinder head construction. But he seriously doubted whether it was now worth while altering the well-developed cylinders now in use, except in detail.

Mr. Tresillian's 24-cylinder arrangement was very interesting and he was glad to have Mr. Tresillian's confirmation that 24 cylinders were sufficient for any engine.

The points raised by Mr. Tresillian on the importance of improving the engineering of the installation and the effect it had on operations was one of the most important and interesting illustrations that had been presented. There was no question about it that an air force in the field had a most onerous maintenance job which, in the author's opinion, meant an unnecessarily big ground staff in relation to flight personnel. He thought that in five or ten years' time, and particularly when gas turbines were in more general use, people would look back and wonder that they ever tolerated the maintenance at present necessary.

In reply to Mr. Duncan, he did not agree that he had been unfair when discussing the relative merits of sleeve valve and poppet valve engines. He had taken great pains to review the merits and demerits of each.

It was not correct to say that the poppet valve had been *developed* over 70 years. As a matter of fact, the (necessary) development of the poppet valve had only been considered properly between the two wars and, roughly, over the same period as the sleeve. It was true that the poppet valve had been in use for many years, but it was not until engine development really advanced that the poppet valve had been attended to seriously rather than tolerated. It was also true to say that a poppet valve engine could be got running more quickly in the development and early production stages than a sleeve valve engine; which latter required generally more development time.

The author saw no advantage in running at piston speeds much in excess of 3,250 ft. per min. And both types of valve in any case could be got to operate equally well at

high speeds, from a mechanical point of view.

During the last year there had been, for the first time in the author's knowledge, an opportunity to compare the relative volumetric and thermal efficiencies of a poppet and sleeve valve engine on a common basis. The two engines concerned had the same bore, but the sleeve valve version had a shorter stroke and ran at a higher crankshaft speed, to give the same piston speed as the poppet valve edition. The poppet valve engine had a compression ratio of 6/1 and the sleeve 6.5/1. Both engines, on 100/130 grade fuel, gave the same power for a given boost, *i.e.*, the boost response, or the powers obtained with increasing boost, were the same for both. The fuel consumption was also similar, despite the fact that the sleeve valve engine was half a ratio higher in compression than its poppet valve counterpart. The explanation was, apparently, that the sleeve valve engine had the higher frictional losses, which balanced out any advantages offered by the increased compression ratio.

The comparisons made by the author were not based on statistics, but upon his own experience, coupled with the experience of others during the present war. He thought statistics were very dangerous things to quote, particularly in regard to aviation engines, unless all the conditions and factors were known. The figures quoted by Mr. Duncan from the S.A.E. Journal could, in the author's opinion, be most misleading. And there had been many cases in the past where a particular engine had given epidemic trouble through some design or development weakness, whereas another engine had not shown up the same weakness. It might, therefore, well be the case that the power plant failures quoted by Mr. Duncan were due to a specific weakness in a particular engine; or might be due to a particularly bad installation which caused engine overheating at a certain operating condition. But the example quoted certainly could not be used to condemn the poppet valve as a whole, particularly in the light of our experience with high duty poppet valve engines in this country.

On the general question of maintenance, it had often been stated that the sleeve valve was superior and needed less maintenance than the poppet valve. Whilst the author had covered this point already in his paper, there was one aspect which was not appreciated.

The airline operating companies often had occasion to remove a cylinder in order to cope with piston trouble. One could do this easily in the case of a poppet valve radial engine. But the removal of the piston presented a problem in the case of the sleeve valve because one could not easily get at the piston after the cylinder had been removed, without disturbing the sleeve.

The author could not agree that, for the same installed weight, the air-cooled engine would have as good a heat capacity factor as the liquid-cooled engine. At least, it yet had to be proved, but the author agreed that a good deal could be done to improve matters.

He agreed that nine cylinders per crankpin had been used and had certainly been satisfactory, but there were more limitations with a large master-rod assembly than with two or four cylinders per crankpin. He agreed that the 18-cylinder radial air-cooled engine still had its place, but did not think an engine with cylinders of 6.5 ins. bore would be very attractive and it would certainly be massive and might have very limited development ahead of it.

He valued very highly Mr. Owner's views because of the latter's experience in design and project engineering. However, in the years he had known him, he had not been aware that Mr. Owner shared his admiration of Lewis Carroll! And his (Mr. Owner's) quotation was very apt.

Replying to Mr. Owner's query regarding the development of each separate section of a new power unit, he thought "unit development" was worth going for provided

it was subjected to such tests that would and could relate to its operation when fitted to the power unit proper. As a matter of fact, in the case of the later piston engines, a good deal of rig testing had been done to prove the efficiency of the supercharger and its mechanical reliability; and this had saved a lot of extra work when the engine was finally built. In answer to Mr. Owner's second point, it was true that development tended towards increased complication, but, as Mr. Owner indicated, there could be a reduction in the amount of complication if careful thought were given to this in the early design stages. However, it seemed inevitable that engines got more complicated as they progressed; due also to the operating requirements of the aircraft user and because any improvement demanded in performance during the life of the aircraft always appeared to fall upon the engine to fulfil.

On the question of fuels for gas turbines, he felt that there would be considerable fuel development even although "detonation" was not a factor. He thought that gas turbine fuels would undoubtedly be safer and present less fire hazard than petrol, and he considered that the fuel companies would be able to give great help in improving the fuel economy of the gas turbine.

The author was glad to have Mr. Ogston's remarks on the fuel aspect. He was also pleased to have some assurance that fuels of a higher grading than 100/130 might become available in sufficient quantities after the war.

In regard to compression ratios, which the author thought would not go much above 7/1, he considered that the "weak mixture" end of the scale should be raised above 100 (possibly to 130) and the "rich mixture" requirement would also be relatively high because of the take-off condition at high boost. Take-off was most important whether for bomber or transport aircraft—nothing paid like pay-load.

Referring to cruising power, the whole point of developing an engine to give a high take-off power was to ensure that it could work at a lower percentage of its take-off power for cruising purposes—to ensure reliability. It did not mean, however, that the cruising power would be low.

The author thought that the figures of 50 and 65 per cent. quoted by Mr. Ogston referred to engines which had a relatively low maximum or take-off power, compared with their size, and in any case an engine that had been well developed to give a high take-off power would be more capable of operating at higher percentages of this power, for cruising, than a big and flabby engine.

He was glad to have Mr. Ogston's views on safety fuels and also fuels for gas turbines. Whether or not the fuel for the gas turbine would be as potent a factor in the development of the latter, as had been so in the case of the petrol engine, was a matter for conjecture.

Dr. Hooker probably had more experience than anyone in this country on the design of successful gas turbines.

Dr. Hooker's example was one which gave a practical illustration of what could be done with the gas turbine and what were the limitations of the piston engine for the particular case cited.

His (Dr. Hooker's) remarks on fuel consumption were interesting. Using stage compressors and turbines, to obtain a higher operating compression ratio, could only give better fuel economy in the case of the propeller/turbine and where little or no jet energy was used. A higher compression ratio would not necessarily benefit the simple turbine/jet engine and the only way in which this latter engine could show an advantage would be at extremely high altitudes and speeds.

The author did not believe that the centrifugal type of compressor was dead by any means. In fact, he thought that there was

a long way to go in getting better axial flow compressors; both as regards their efficiency and their practicability.

Lieut. Robinson had raised a very important point in regard to the propeller/turbine and if his suggestion were possible, practically, it would considerably alter the picture in regard to the use of turbines for the more moderate speeds at lower altitudes. And where, at present, the piston engine appeared still to have the advantage.

The author agreed with Lieut. Robinson in regard to the effect which the gas turbine would have upon propeller design. It should be possible to make lighter and more efficient propellers.

Mr. Bass amplified the points made in the paper on lead distribution and he showed how carefully one must go when evaluating single cylinder tests to correlate with tests on the full-scale engine.

The author was glad to have Mr. Bass's confirmation that a good deal of work would have to be done on safety fuels before they could be used properly. And, even with individual cylinder injection, there would be starting difficulties and, possibly, normal volatility fuel would have to be used to obtain a start. But, once started, the author did not necessarily agree that there need be a drop in performance or increase in specific fuel consumption with safety fuel, if the injection system were properly developed.

In regard to the combined piston/turbine power unit, the author did not consider it as an interim engine and thought that it would be well worth while for aircraft of extreme range. Possibly it would only be used for military aircraft. Such a power unit would not be attractive to the passenger transport people once they had experienced the vibrationless operation of the gas turbine.

Referring to the last paragraph of Mr. Bass's contribution, he still felt that fuels for the gas turbine would perhaps become more expensive than was at present envisaged and he was sorry that Mr. Bass deplored the use of additives. There was nothing against additives if they offered improved performance. There were two possibilities: (*a*) an additive which would speed up combustion in order that the shortest possible combustion chamber could be used and so cut the length and, therefore, the weight, of the gas turbine as a whole; and (*b*) an additive to increase the volumetric heat value of the fuel and so compensate for the relatively high fuel consumption of the gas turbine. This latter would undoubtedly involve long-term investigation.

Both Mr. Parkes and Mr. Cleaver made some valuable points on different but important aspects of propellers.

It was the author's opinion that the propeller was by no means dead and there would possibly be more applications for the propeller/turbine than for the simple turbine/jet. The propeller people could, he thought, contribute a great deal and he wanted them to look into the question of propeller efficiencies for high forward speeds, up to about 550 miles per hour.

In reply to Mr. Lucas, the author said that he had some sympathy for Mr. Lucas and the troubles of a test pilot engaged on prototype work. But there was, in his opinion, a reasonable explanation as to why the bulk of the problems were centred around the engine and its installation, since the engine was "dynamic," whereas the airframe was in a sense a "static" structure. There would always be in his opinion more problems on the engine and engine installation side than with the airframe. That was not to say that there were no troubles with the airframe—there were plenty—but they generally occurred at the commencement of a new phase in aircraft performance and mainly were connected with increase in speed.

Not all the blame could, however, be placed on the engine man, since it was the

author's opinion that, in many cases, the aircraft designer did not keep good liaison with the engine manufacturer, nor did he always profit from past experience.

Mr. Pobjoy had given some interesting information and the author was little at variance with him. On the question of engine weight, the author meant all-out level power and not take-off power.

Referring to the last paragraph of Mr. Pobjoy's contribution, he confirmed that the use of safety fuels would considerably reduce the risk of vapour locks in the fuel system and, in fact, they should not occur at all with a properly designed system.

Squadron-Leader Samaras's contribution was a valuable addition to the discussion, on a number of important points. He (the author) did not necessarily agree, however, that the piston type engine would always predominate at the lower altitudes and speeds.

The author respected Mr. Morley's opinions, and while he agreed with Mr. Morley that there were many problems to solve before they knew what the gas turbine was worth, he felt that they would be solved and there would probably be fewer headaches in the development of the gas turbine than there had been with the high duty piston engine. He did not agree with Mr. Morley that the simple turbine/jet would be the only type of turbine for some time to come. Propeller/turbines were in the offing and although there were more problems associated with their development, he felt that they would have equal development and use in the next five years or so.

On the question of fuels for the further development of the piston engine, the author anticipated no difficulty in obtaining fuels of high anti-knock value when required.

The points mentioned by Mr. Hartshorn emphasised the need for trying out on the orange analogy, *i.e.*, " sucking and seeing." In other words, aircraft must be built with turbine engines tailor-made to suit them, and only then could they be compared with the more conventional aircraft of to-day. But it spoke well of the turbine that, with the relatively small experience we had of it to date, an aircraft could be designed with turbine engines and be expected to perform according to estimation.

He thanked Mr. Sammons for the points he raised in his written contribution and for his kind remarks regarding the paper.

It would be most unusual in the history of aviation if the gas turbine did not become more complicated as its development progressed. But apparent complication was not detrimental provided development was sound —otherwise we might well be keeping to six-cylinder engines in aircraft and one- or two-cylinder engines in motor cars.

He was at one with Mr. Sammons in trying to achieve a high state of economy in operational costs, and he was also against State subsidies where they could be avoided.

On the question of safety, the author felt that there was no inherently safe type of aviation engine or aeroplane; assuming, even, that the combination of engine and airframe fully met design and operational requirements. The only way to obtain safety in the air was by meticulous attention to detail. Materials, design, development and manufacture must be most carefully done, and, then, only well-trained personnel in the air and on the ground, also controlled by fairly rigid rules, could ensure some reasonable degree of safety in air travel.

In reply to Mr. Aherne Heron, the author felt that there was still further necessary development work to be done in the case of the piston engine, and the piston engine would still be used for some years to come. He felt also that the hollow steel propeller

blade would eventually be used for very high-speed aircraft since it was so necessary to have rigidity with the extremely thin blades, working at high Mach number.

As stated in his replies to other contributors to the discussion, the author felt that simplicity, although desirable, was not necessarily the criterion of a good engine. Aviation engines must be good performers, and if, to obtain the best results, a certain degree of complexity was necessary, then it must be seriously considered.

In reply to Mr. Lowrey, he could not agree that time-tables or target dates were " intolerable " when a new design of engine was being developed. It was too often the case that people were imbued with the old Chinese idea of time. But there was nothing like a time-table or a series of target dates to keep people on their toes. Maybe, in the case of an entirely new type of engine, it was not possible to keep to the dates laid down, but nevertheless there should always be a time-table for industrial development.

In regard to the compression ignition engine, the author referred Mr. Lowrey to his (the author's) reply to Dr. Ricardo; and reiterated his point of view that there was no place for the C.I. engine in aviation except, possibly, in combination with a gas turbine.

The author referred Group-Capt. Scroggs to his reply to Group-Capt. Bulman on the question of power units and power plants. But the author was in full agreement with Group-Capt. Scroggs that the engine installation was a source of considerable trouble, and the situation was still not at all happy. More attention was now being focused on the engine installation and he hoped that something would soon come of it.

Group-Capt. Scroggs, like Group-Capt. Bulman, appeared to miss the point of the paper, which was concerned with the type of power unit to come, and not how it was to be engineered as an installation.

He agreed that neither " power per square inch of piston area " nor " lbs. per b.h.p. hour " were of particular interest to the aircraft operator, when put in that form. But the shape and bulk of the eventual engine was of considerable importance to the aircraft designer and indirectly to the operator.

Group-Capt. Scroggs was an experienced pilot and the author respected his views on the subject of air- and liquid-cooled engines. The author preferred the liquid-cooled engine for all-round performance, but, for special purposes, such as ground-strafing, it appeared that the air-cooled engine had considerable advantages and was less vulnerable to "flak" and bullets than the liquid-cooled job.

Note on AIRCRAFT STRUCTURAL FAILURES *and* FACTORS FOR SAFETY

by

Squadron-Leader J. G. M. Pardoe

Squadron-Leader J. G. M. Pardoe, an Associate Fellow of the Society since 1942, has been serving as an Inspector of Accidents at the Air Ministry. Before the war he was employed by Vickers' Supermarine and the Heston Aircraft Co. on the strength of prototype aircraft.

Introduction

1. The well-known maxim " know your enemy " is as sound in aircraft design as it is in war. Application of this doctrine might perhaps modify the conclusions in Mr. Tye's interesting paper, " Factors of Safety —or of Habit?" published in the November issue of the Journal. He discussed design factors and strength requirements from the aspects of V-g records and of structural variation. The V-g records with very few exceptions have been obtained from aircraft which have not broken up. " The enemy," however, is structural failure and much can be learned by study of the reasons for and nature of the failures that have occurred. The conclusions that may be drawn are perhaps less pessimistic than those of Mr. Tye. Under the present requirements his statement that " It is impracticable to build aeroplanes so strong that they cannot be broken," is not in dispute. I think, however, that accident analysis may show that it should be possible to design aircraft that will never achieve loadings of sufficient magnitude to break a structure of economical strength and that to design for an expected failure rate is not only unduly pessimistic, but also impossible.

2. It is obviously not permissible at the moment to publish detailed information and statistics concerning the failures that have occurred, but I think that what may be said in general terms is relevant and may be of interest.

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Structural Failures

3. I think it can fairly be stated that:—

(*a*) In the great majority of cases in which the main structure has failed it has not done so until outside the design n-V envelope. Although there is a small proportion of cases when failure has been due to faulty manufacture or design it has been due mostly to bolts dropping out or fatigue at a comparatively low factor and has been independent of ultimate factor or speed, so need not be considered in an argument on factors.

(*b*) Failures of the secondary structure, such as skin wrinkling and cracking, stressed detachable panels working loose, rivets and bolts " working " are far more numerous and are caused both by exceeding the design conditions and many, especially of the heavy aircraft with lower factors, by often repeated loads of below the design proof and probably of less than half the ultimate.

4. The failures due to exceeding the n-V limitations fall almost completely into two classes.

1. Those in which the first failure is that of the wings upward due to excessive "g."

2. Those in which speed causes failure or distortion of any part of the aircraft, which leads to a change of loading or attitude at which comprehensive failure occurs.

There is a great difference between the manœuvrable classes of aircraft types with low stick forces per "g" and the " heavies " with heavier controls. In the former there is evidence to suggest that all values of "g," and often of V, from those of normal usage to those just on the point of failure, are attained and that recovery is effected. In our " heavies," however, this is seldom the case. There is the same evidence that the increasing values of "g" and V decrease in frequency, but then there is evidence of a gap from the highest recorded values in normal use to a much higher value at which failure occurs. There is also evidence that frequency of failure may be considerably greater than that at which the higher values are attained in normal use. Two types of accident are quoted below to illustrate this phenomenon with respect to the two classes of failure mentioned. It is encouraging to note that aircraft have seldom, if ever, been found prone to both types of failure and there is no reason to believe that curing one type need necessarily lead to the other.

1. Aircraft of some types may never exceed a normal factor of 2/3 the ultimate unless they are going to exceed the ultimate and break-up. This might be caused by structural deformation increasing the applied loading, but is in fact likely to be due to the flying characteristics of the aircraft. The pilot has not sufficient strength to impose excessive "g" with the aircraft in a normal attitude, but in certain conditions the aircraft will increase "g" on its own and recovery may become beyond the pilot's capability, while "g" goes on increasing until failure occurs.

2. If aircraft of a type are unstable in the dive or near the design V max. deformation (not necessarily of the main structure) occurs and alters the stability, the speed tends to rise still more and recovery becomes increasingly difficult or impossible, while the speed goes on increasing until failure occurs or the ground intervenes.

5. In the " heavies " class it seems probable that V-G records can show the limits and frequencies of conditions imposed directly by pilots' efforts or gusts, but that they cannot indicate the frequency of the catastrophic conditions which cause the majority of complete failures. It is true that these conditions practically only arise after loss of control by the pilot, but in some circumstances temporary loss of control must be faced as being sometimes unavoidable, e.g., circumstances such as unforecast weather and icing, stalling in a violent turn to avoid collision, outer engine failure and/or runaway propeller, failure of B.F. instruments, etc. However, that temporary loss of control should not necessarily lead to structural failure is shown by the wide variation of the accident rates for different types of aircraft of the same strength and class used in the same circumstances. The structural failure rate seems to be dependent on the aerodynamic characteristics of the aircraft and if the rate is high it is almost certain to be because of some unfortunate characteristic, e.g., a tendency to tighten in a spiral, change of stability at high speed, control system distortion or overbalance or possibly high mach number effects. It is probable that this is also true of a perhaps high proportion of the failures of the manœuvrable types of aircraft, the failures of which have been more often attributed directly to the pilot's handling. This could account for the often great variation in rates and type of failure between not only aircraft in the same class, but also between different marks of the same aircraft type.

Factors for Safety

6. From the foregoing it would appear that the strength required can be considered for two main cases:—

(*a*) The ultimate strength needed to avoid failure of the structure due to mishandling by the pilot or due to any dangerous tendencies the aircraft may have to produce high "g" or V.

(*b*) The proof strength necessary to cover the "g" and V of normal use.

These strengths may be laid down by means of n-V envelopes. That for the proof condition could be obtained from operational requirements and past experience, of which V-"g" records, with due allowance for stick force, etc., are a most valuable part. For the diagram for the ultimate strength I am most strongly in agreement with Mr. Tye's suggestion that it is up to the designer to produce the evidence on which it is based. That " My aeroplane must be expected to break-up every so often " should not, however, be the evidence as much as " My aeroplane cannot be subject to more than x 'g' and y V; therefore such and such a strength will be required." That these requirements are in the right direction is, I think, shown by the evidence from accident investigation, i.e., that structural failure is at least as dependent on the flying characteristics of an aircraft as on its strength.

7. The requirements suggested above raise many controversial possibilities and I fear barely touch the fringe of the problem of factors. For instance, they would make "g" restrictors and possibly other forms of gadgetry a good proposition from the weight point of view. It does, however, seem more logical to aim at designing aircraft not to incur excessive loading than to carry the weight of the strength necessary to prevent failure when the aircraft are uselessly exceeding their operational requirements.

8. The evidence for deciding the n-V envelope for small aircraft might have to be that of habit, but in the heavy classes, if aviation is to become a commercial proposition, efficiency and safety will be worth considerable effort. With the aid of reduced scale test aircraft (with increased strength and escape exits) a series of handling and mishandling tests might provide an assessment of the V and "g" to be catered for on the full-scale machine. Such research would be expensive, but—under the control of the licensing authority and with the results made available to the whole industry—it should be of national benefit and the cost might be defrayed by the exchequer.

9. It is necessary in most designs to know at an early stage the strength for which to cater; also most designers are optimists. In these circumstances it is likely that a low ultimate strength would be chosen in the first place and the research would be used to justify the choice. This might lead to some costly failures, but it is better, when possible, to reject an aircraft until it is safe than to modify it after it has had a tragic history.

10. The requirements suggested in para. 6 give no fixed ratio between proof and ultimate strengths. For any actual design a definite ratio is probably desirable, but, as the proof and ultimate are required to meet different conditions, the ratio could perhaps most efficiently be decided after consideration of the shapes of the design envelopes and the properties of the materials to be used in the structure. Mr. Tye makes the point that if aircraft are to be designed to " use " all the proof strength the factor of safety on the present military ratio of proof to ultimate would become 1.33 not 2.0 as in the past. In respect of this it is interesting to note the pilots' attitude of mind. I think very few pilots have any idea that their machines were designed for certain "g" and V and then to have a factor of safety of 2.0. Few pilots indeed have any accurate quantitative idea of "g," and most judge the strength of their

aircraft on the manœuvres that they have been taught they may carry out or that they have found by experience do not produce permanent distortion of the aircraft.

Conclusions

11. (*a*) The structural failure rates for most types of aircraft, at the strength factors now in use, depend more on the flying characteristics of the aircraft than they would on even quite large variation of the structural strength.

(*b*) Before it may be possible to prophesy structural failure rates considerable improvement will have to be effected in the characteristics likely to cause loss of control and in the behaviour of aircraft after control has been lost.

(This conclusion may not apply to large commercial aircraft. Pilots of proved ability, duplication of instruments and strict ground control may assure that control is never lost.)

(*c*) To avoid both failure and inefficiency it seems desirable to consider an aircraft's probable individual characteristics when deciding on the strength required.

I am indebted to the Chief Inspector of Accidents for permission to submit this note. The opinions expressed, however, are my own and must not be taken as official.

VALUE OF WEIGHT SAVING IN AIR LINERS

by
Major F. M. Green

Major F. M. Green went to Farnborough in January, 1910, as Engineer in charge of design, and was responsible for the aircraft and engines produced there for the next seven years. On the stopping of design by the Government he became Chief Engineer of Armstrong Siddeley Motors and Sir W. G. Armstrong Whitworth Aircraft, where he was responsible for the famous Argosy class air liner and the Atlanta. Major Green is again back at Farnborough as a consultant.

Summary

THE value of 1 lb. of weight saved in an air liner has been given as equal to 1 lb. of gold in an American paper. This figure has been calculated in a more complete way, and on the assumptions made is reduced to £16 10s. or near enough to one guinea per oz. saved.

(1) It is almost always possible to reduce the weight of any component of an aircraft or engine by refining the design. This can be done in many ways, but chiefly by improved material, by reducing dimensional tolerances, by more accurate stressing and by development by mechanical testing. These processes increase the cost and time of manufacture, and as the value of an air liner starts only when it is put into service, and its useful life is settled by obsolescence rather than by wearing out, there is always a practical limit to the time that can be spent on design, development and manufacture. During wartime the resources of the country are pushed to their limit and it is often impossible to get a big enough production of the best materials, or to work to fine tolerances; hence we accept an aircraft a good deal short of the ideal. The life of the aircraft is comparatively short and is governed largely by factors outside our control, so that an assessment of the value of weight saving is nearly impossible.

It is quite otherwise with civil air liners. Reliable statistics of the life, earning power and cost of operation are available for the D.C.3 used on internal air lines in the U.S.A. These are given in Warner's Wilbur Wright Lecture of 1943. It is possible to estimate the value of weight saving and to get a figure for the cash value of each lb. saved, which will be at least of the right order. In an American journal, the author suggests that each lb. saved is worth its weight in gold, which is at present values about £150. This is an astonishing figure, and if it were true there is practically no expense in saving weight that cannot be justified.

The assumptions by which this value was obtained were that an air liner during its useful life would travel 4,000,000 miles, carrying an average of 60 per cent. of its full load at five cents. per mile per passenger of 200 lb. weight. The total revenue will then be $600 per lb. which is $37.5 per oz., near enough to the present price of gold. This calculation is too simple because many relevant factors are ignored which reduce the figure to a more reasonable value. The figure has been recalculated in an endeavour

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to get nearer the real value by the following method.

2. (i) Only a part of the total expense of operating is chargeable to the aircraft itself, i.e., is dependent on the air miles flown and percentage payload. Warner suggests 40 per cent. for this, the remainder being overhead charges depending chiefly on the number of passengers carried.

(ii) The allowance of 200 lb. per passenger is misleading. If extra passengers are carried, allowance must be made for extra passenger fittings, say 80 lb., and for the extra weight of the larger fuselage to carry them, and this is estimated also at 80 lb. per passenger. Some allowance must also be made for the extra drag of the larger fuselage, and for the extra fuel and larger engines to overcome this. Actually this allowance is small and is easily covered by adding 20 lb. to the weight of the passenger for aircraft flying on routes up to 1,000 miles. 200 lb. a passenger is rather low if baggage is included. If we make this 220 lb. the equivalent weight per passenger with the above additions becomes 400 lb. or double the American figure.

(iii) If the various components are lightened, they will generally cost more to make, so that the cost of spares will be increased, depending largely on the degree to which lightness can be carried. It is very difficult to assess this extra cost and the estimate used, which is largely a guess, is £6 per lb. of weight saved, which is possibly on the high side.

(iv) The lighter aircraft will cost more and this extra cost will only be repaid during the lifetime of the air liner which is taken to be five years. Hence we must deduct interest on the extra first cost for $2\frac{1}{2}$ years which at 5 per cent. means a reduction of $12\frac{1}{2}$ per cent. on the estimated saving.

3. The actual figures with the corrections above, based on a lower mileage than in the American estimate, are as follows:

Revenue per passenger mile assumed—3d. which is the probable operating cost + 10 per cent.
Average number of passengers carried—2/3 full load.
Flying hours per year—3,000.
Cruising speed—200 m.p.h.
Life of aircraft—5 years.
Total miles flown—3,000,000.
Total revenue per passenger seat—6,000,000d.
Equivalent weight of passenger (see para. 2 (ii))—400 lb.
Revenue per lb. of equivalent passenger—15,000d.

Of the above, only 40 per cent. is chargeable to aircraft running expenses, so the value per lb. saved must be reduced to 6,000d. which is £25. From this we must subtract the increased cost of spares which is £6, so that the saving is again reduced to £19. Once again we must subtract $12\frac{1}{2}$ per cent. of this for interest on the money due to the extra cost of the aeroplane; this reduces the figure to £16 10s., or say one guinea for every oz. saved. This is not an exact figure, it depends on the assumptions of mileage during the life of the air liner, the fares charged and the average percentage of full load. It is little more than 1/10 of the American estimate, but it is still surprisingly large. If we accept it as being of the right order, it means that when the country is not working at its maximum capacity, it will pay to decrease aircraft weights by the intensive study of everything that goes to make up a passenger air liner even at the expense of considerable increase of cost. This applies much more to parts usually described as non-stressed than to highly stressed components. Such things as wing spars are probably not far off their minimum weight, because the distribution of stress in them has been thoroughly studied. But spars only amount to about 5 per cent. of the empty weight of the air liner, so it seems that a

study of the design of other things will be much more profitable than attempting to fine down the main structure. The aircraft designer's difficulty is that much of the equipment is not under his control and he has to put up with gear which is not designed down to anything like minimum weight. If a bonus were paid to the manufacturer of such things as radio, electrics, landing gears, etc., on the basis of even as little as £5 per lb. of weight saved there would almost certainly be a rapid reduction in the weight of equipment and the air line operator would be very much in pocket. As an example, if a component costs at present £2 a lb. weight, a 10 per cent. weight saving would increase price by 25 per cent. for the supplier, while the operator would benefit it in the long run by twice as much.

·4. At the end of the war there will be large stocks of equipment for disposal at very low prices. If these have to be absorbed before there is a demand for new material, it will be unfortunate for aircraft makers, who will be short of work. If any component can be lightened by 20 per cent., then assuming the value of one guinea per oz. saved to be correct, it will just pay the operator to scrap an existing component, if the new one costs £3 per lb. or less. This applies correctly only to aircraft being designed, as it is assumed that the cabin is enlarged to house the extra passengers or freight that can be carried. The precise value for an existing air liner will depend on whether there is room enough to carry the extra passengers or freight made possible by the use of lighter components, and also on the length of the unexpired life of the aircraft, if it is already in service.

(Correspondence on this paper is invited.)

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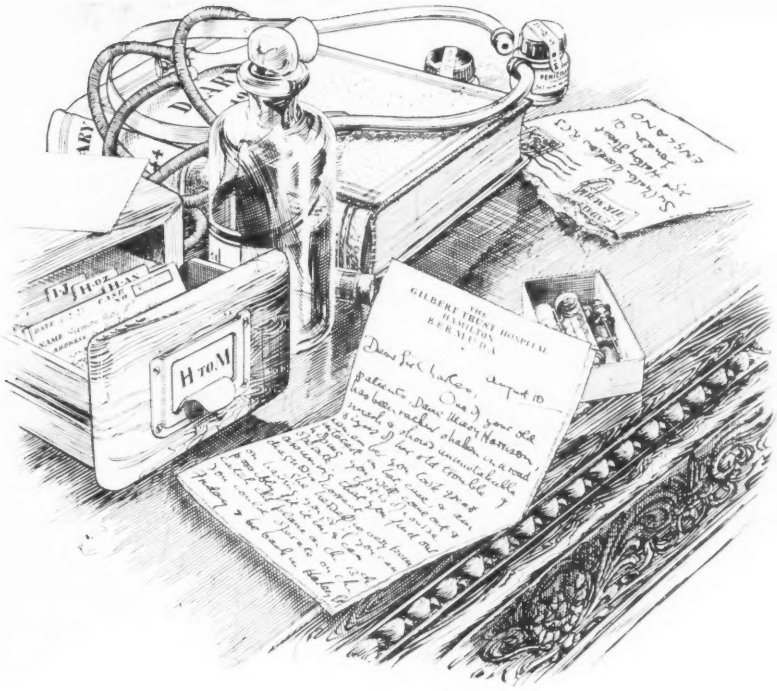

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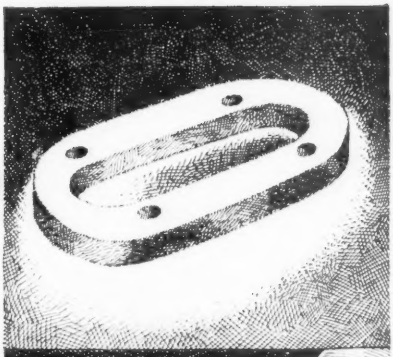

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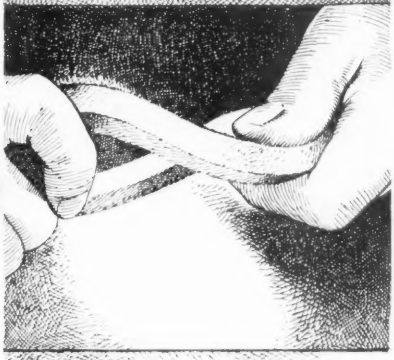

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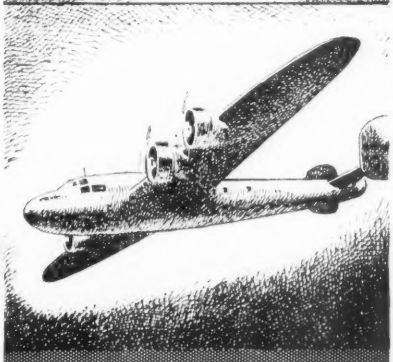

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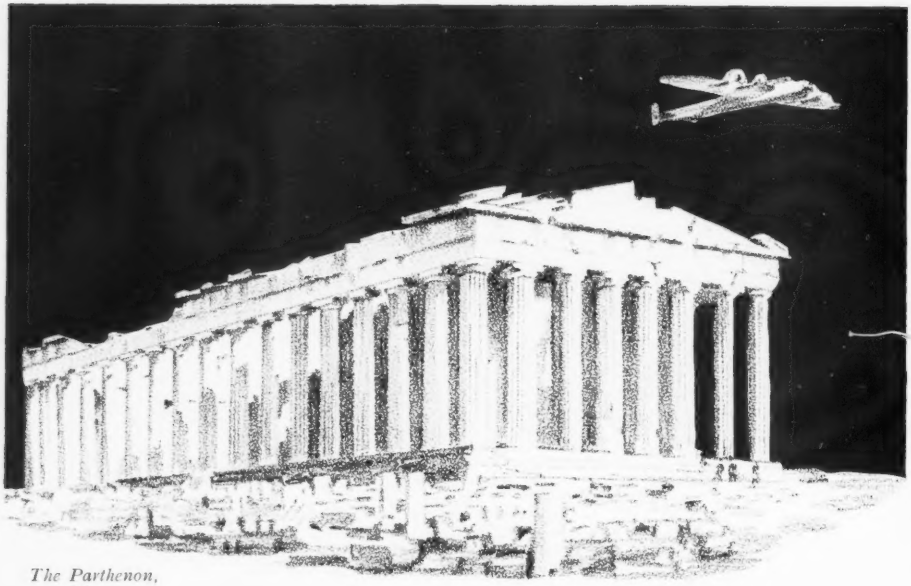

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